# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## TECHNICAL NOTE 3198

## DYNAMIC STABILITY AND CONTROL CHARACTERISTICS OF A CASCADE-WING VERTICALLY RISING AIRPLANE MODEL IN TAKE-OFFS, LANDINGS, AND HOVERING FLIGHT

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## SUMMARY

An investigation has been conducted by means of tests of a flying model in still air to determine the dynamic stability and control characteristics of a cascade-wing vertically rising airplane in the take-off, landing, and hovering phases of flight. The model had four propellers with thrust axes essentially parallel to the fuselage axis and distributed along the span so that the wings were completely immersed in the slipstream. The model had four wings arranged in a cascade relation to turn the slipstream downward approximately 90° to produce direct lift for hovering flight with the propeller thrust axis essentially horizontal.

It was almost impossible for the pilot to fly the model without the use of artificial damping in pitch, because of a violently unstable pitching oscillation. This oscillation could be stabilized by the use of a rate-sensitive artificial damper, which made the pitching motions easy to control. The rolling motion was slightly divergent, but was easy to control without any artificial stabilizing device. The model apparently had considerable damping in yaw and the yawing motions could be controlled easily. Vertical take-offs and landings could be performed satisfactorily. The only unusual behavior noted when flying near the ground was a slight tendency to pitch nose-down and move forward when the model was trimmed for hovering flight well above the ground. Some difficulty was experienced in controlling the vertical motions of the model, apparently because there was little damping of these motions.

## INTRODUCTION

The concept of a vertically rising airplane which can take off and land vertically like a helicopter and can achieve high forward speeds like an airplane is not new. A great many designs of such aircraft have been proposed in the past. To produce direct lift, all that is necessary is to impart a sufficient downward acceleration to a sufficient mass of air. In the case of a helicopter a large mass of air is moved with relatively low power at low velocity by means of a large rotor, whereas in the case of an airplane a smaller mass of air is moved at higher velocity with a propeller. In order to achieve sufficient direct lift for hovering with reasonable-size propellers, it is necessary to have an airplane with a very high power-to-weight ratio. The recent development of turboprop engines has made such power-to-weight ratios possible and has consequently caused increased interest in vertically rising airplanes.

There are basically two methods of directing the slipstream downward: (1) for the whole or part of the airplane to tilt so that the propellers are in a horizontal plane, and (2) for the wing and flaps of the airplane to redirect the slipstream of conventionally located propellers. In order to obtain basic information on the stability and control characteristics of this second type an experimental investigation has been made with a flying model in the take-off, landing, and hovering phases of flight.

The model was a simplified design which was intended only for hovering flight and was not intended to represent a practical configuration for a full-scale airplane. It had four propellers with their thrust axes essentially parallel to the fuselage axis and distributed along the span so that the wings were completely immersed in the slipstream. The model had four wings arranged in a cascade relation to turn the slipstream approximately 90° downward to produce direct lift for hovering flight with the propeller thrust axes essentially horizontal. The model was controlled by means of trailing-edge flaps and variable-pitch propellers.

The investigation consisted of hovering flights in still air at a considerable height above the ground, hovering flights very close to the ground, and vertical take-offs and landings. The investigation included a study of the effect on the stability of the model of various amounts of artificial damping in pitch and roll. The stability, controllability, and general flight behavior of the model were determined from motion-picture records, visual observation of the flight tests, and from pilots' impressions of the flying qualities of the model. A few force tests were also made to determine the static effectiveness of the controls used in the flight tests.

Some supplementary force tests were made for various wing and flap configurations to find a wing configuration that was reasonably efficient in deflecting propeller thrust and with which sufficient control effectiveness could be obtained. The results of these tests are presented in an appendix.

# SYMBOLS

All forces and moments are referred to the body axes. Figure 1 shows these axes and the positive direction of the forces, moments, and angular displacements. Linear displacements in time histories of the model motions are presented with reference to horizontal and vertical space axes.

The definitions of the symbols used in the present paper are as follows:

$\theta$ angle of pitch of thrust axis relative to horizontal, deg

$\dot{\theta}$ pitching velocity, deg/sec

$\psi$ angle of yaw, deg

$\phi$ angle of bank, deg

$\dot{\phi}$ rolling velocity, deg/sec

$\delta$ deflection of flap on vane of a cascade wing (with subscripts indentified in sketches as used), deg

$\delta_p$ pitch-flap deflection (trailing-edge-forward deflection is positive), deg

$\delta_v$ deflection from initial position of each vane that is deflected in a cascade of airfoils (trailing-edge-forward deflection is positive), deg

$\beta$ propeller blade angle, deg

L' rolling moment, ft-lb

M pitching moment, ft-lb

N yawing moment, ft-lb

W weight, lb

$I_X$ moment of inertia about X-axis, slug-ft$^2$

$I_Y$ moment of inertia about Y-axis, slug-ft$^2$

$I_Z$ moment of inertia about Z-axis, slug-ft$^2$

X longitudinal force, positive forward, lb

Y lateral force, positive to right, lb

Z normal force, positive downward, lb

L lift, lb

D drag, lb

T thrust, lb

## MODEL

The model was a simplified research vehicle for use in an investigation of some of the basic stability and control problems of the type of vertically rising airplane in which the propeller slipstream is turned downward by the wings. Photographs of the model are presented in figure 2 and a three-view drawing is presented in figure 3. The configuration of the model was chosen on the basis of some of the preliminary force tests described in the appendix as one which had reasonable efficiency for hovering flight and with which it seemed possible to obtain adequate control moments. No attempt was made in this preliminary investigation to obtain an optimum configuration and the model configuration selected was not intended to represent that of a practical design. In fact, the airfoil section of the wings was that of a wind-tunnel turning vane which could not be uncambered for forward flight.

The flying model had four propellers with their thrust axes essentially parallel to the fuselage axis and distributed along the wing span, so that the wings were completely immersed in the slipstream. There were four wings arranged in a cascade relation to turn the slipstream approximately 90° downward to produce direct-lift for hovering flight with the propeller thrust axes essentially horizontal. Details of the airfoil and wing arrangement are given in figure 4. The airfoil section used for the wings was similar to the wind-tunnel turning vane, section C, given in reference 1. The model motor was a 5-horsepower variable-frequency electric motor which drove the four propellers through shafting and right-angle gear boxes. The speed of the motor was changed to vary the thrust of the propellers.

Pitch control was obtained by deflecting a full-span flap on the lowest wing. (See fig. 3.) A deflection of this flap tilted the resultant force vector of the lower wing so that it produced a pitching moment. A positive flap deflection (trailing edge forward) caused the resultant force vector to be inclined more rearward and thereby produced a nose-down moment (negative pitching moment). Conversely, a negative (trailing edge rearward) flap deflection produced a nose-up moment (positive pitching moment).

Yaw control was obtained by a differential deflection of outboard flaps on the three upper wings. These flaps covered the outboard 12.12 inches of the span. Positive deflection (trailing edge forward) of the flaps on the left wing and negative deflection of the flaps on the right wing produced a negative yawing moment since the resultant force vector on the left wings tilted more rearward and the resultant force vector on the right wing tilted more forward. Positive yawing was of course obtained by the reverse of this deflection.

Roll control was obtained by varying the total pitch of the two outboard propellers differentially. Increasing the pitch of the left outboard propeller and decreasing the pitch of the right outboard propeller increased the lift on the left wings and decreased the lift on the right wings and thereby produced a positive rolling moment. Negative rolling was obtained by the reverse of this process.

The controls were operated remotely by the pilots by means of flicker-type (full on, full off) pneumatic servomechanisms which were actuated by electric solenoids. These manually operated servomechanisms gave approximately the following control deflections:

| | |
|---|---|
| Pitch flap, deg | ±14 |
| Yaw flaps (each flap), deg | ±18 |
| Outboard propeller blades (each propeller), deg | ±3 |

In some flights rate-sensitive artificial stabilizing devices were used to increase the damping of the rolling and pitching motions. These devices (called roll or pitch dampers) consisted of gyroscopes which, in response to rate of roll or pitch, provided signals to proportional control actuators which moved the controls to oppose the rolling or pitching motion. These proportional control actuators were connected to the flicker actuators so that their outputs were superimposed. The pilot could therefore bias the output of this double control actuator and impose manual control while the damper was operating. The control deflection provided by the artificial stabilizing devices was in addition to that provided by the manual control mechanisms so that the total control travels with the stabilizing devices operating were greater than those previously given for the manual control alone. The maximum additional deflection that could be provided by the pitch and roll stabilization devices were:

Pitch-flap deflection, deg . . . . . . . . . . . . . . . . . . . . . . . . . ±11
Outboard propeller blades (each propeller), deg . . . . . . . . . . ±2

For most of the tests the center of gravity of the model was located in the plane of the propeller shaft axes and 7.90 inches behind the leading edge of the bottom wing. (See fig. 3.) For a few of the flight tests which will be specifically pointed out in the discussion of results, the center of gravity appeared from the flight results to have been farther rearward than this location. These tests were made at a considerably later time than the original tests and after the model had been rebuilt for use in some demonstrations. No measurements of this center-of-gravity location were made, but the difference in the trim pitch angle in these later flights indicated a different location. The weight of the model was approximately 31 pounds. The moments of inertia were approximately:

$I_X$, slug-ft$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1.43
$I_Y$, slug-ft$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . 0.90
$I_Z$, slug-ft$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1.87

A few preliminary force tests were made with some simplified models which consisted of short-span cascade wings of various designs and a single propeller. Since there were a number of these configurations and since these tests are considered of secondary importance in the present paper, these models are described in an appendix together with the test results.

## TEST EQUIPMENT

The investigation was conducted in the facility used by the Langley Free-Flight Tunnel Section for flight testing hovering models using the test setup illustrated in figure 5. This facility has a useful test space of approximately 48 by 70 feet in plan and 50 feet high which is located in a large building that provides protection from outside air turbulence and inclement weather.

The power for the motor and electric solenoids and the air for the servomechanisms were supplied through wires and plastic tubes. These wires and tubes were suspended from above and taped to a safety cable (1/16-inch braided aircraft cable) from a point about 15 feet above the model down to the model itself. The safety cable which was attached to the fuselage near the center of gravity was used to prevent crashes in case of control failure or in case the motions of the model were very unstable. During flight the cable was kept slack so that it did not appreciably influence the motions of the model. A propeller guard (shown in figs. 2 and 5) was mounted above the propellers to prevent any excess slack of the flight cable from falling into the propellers. The propeller guard was essentially a 2-foot-diameter screen made up of 1/16-inch-diameter wire and mounted atop a rigid post.

Force tests of the models were made in the same test area used for flying the model. These tests were made with the strain-gage balances generally used in the Langley free-flight tunnel for force tests.

## FLIGHT TEST TECHNIQUE

Separate pilots operated the pitch, roll, and yaw controls in order that careful attention might be given to the study of the motions of the model about each of these three axes. Two other operators in addition to the pilots were used in flying the model: one to control the power to the propellers and one to operate the safety cable. The pilots and power operator were the principal observers because they had control of the model and could obtain qualitative indications of the stability, controllability, and general flight behavior.

The test technique will be explained by describing a typical hovering flight. The model hangs on a safety cable and the power is increased until the model climbs to the desired altitude. The safety cable is allowed to hang slack over the propeller guard and the safety cable operator then recovers any excess slack or releases more cable as required during the flight. During the flight the power is regulated to keep the model at the desired altitude. The pilots keep the model as near the center of the test area as possible during the climb. When the desired height has been reached the pilots establish a steady hovering condition by carefully trimming the controls. Then they perform the maneuvers required for the particular tests and observe the stability and control characteristics.

In order to determine the stability of the model for unstable conditions, the pilots allow it to fly uncontrolled for as long as possible starting from as near a perfectly still and trimmed condition as they can establish. These tests are terminated when the model moves off too far from the center of the test area and is in danger of striking the walls of the building or some other obstruction. Motion-picture records of these uncontrolled motions are made for quantitative study. For stable motions the pilots disturb the model, after carefully trimming it, and the decay of the subsequent motions is noted.

Vertical take-offs from the ground were made by rapidly increasing the speed of the propellers until the model took off. These take-offs were rather abrupt and the model generally climbed to a height of about 10 feet before the power operator adjusted the power for steady hovering flight.

Landings were made by decreasing the speed of the propellers so that the model descended slowly until the landing gear was about 1 foot above the ground. At this point the power was cut off completely and the model dropped to the ground.

The speed of the model motor, and consequently the lift of the model, was controlled by varying the speed of the variable-frequency motor-generator set which supplied current to the motor. Since the elements of the motor-generator set were standard heavy-duty pieces of equipment, the time required for the set to change speed plus the time required for the model motor to change speed introduced considerable time lag in the control of the thrust of the model.

## TESTS

The tests included hovering flight at a considerable height above the ground, hovering flight near the ground, and vertical take-off and landing. The stability, controllability, and the general flight behavior of the model were determined in various cases, either qualitatively from the pilots' observations or quantitatively from motion-picture records of the flights. General flight behavior is the term used to describe the overall flying characteristics of a model and indicates the ease with which the model can be flown. In effect, the general flight behavior is much the same as the pilot's opinion of the flying qualities of an airplane and indicates whether stability and controllability are adequate and properly proportioned.

The hovering flight tests made at a considerable height above the ground (approximately 15 feet) were conducted to determine the basic stability and control characteristics of the model. That is, they were made to determine how the model behaved in controlled flight and to determine the nature of its uncontrolled motions, when it was far enough away from surrounding objects to eliminate effectively any outside interference effects and when no artificial stabilizing devices were used.

The effects of artificial stabilizing devices in pitch and roll were also determined in hovering tests at altitude. The tests with the pitch damper were made for a range of values of the response parameter $d\delta_p/d\dot{\theta}$ from approximately 0.2 to 0.6, but the tests with the roll damper were made for only a value of the response parameter $d\beta/d\dot{\phi}$ of about 0.4. The values of the response parameters were obtained by calibrating the dampers on a rocking table.

The effects of ground proximity on the stability and control characteristics of the model were determined by making hovering flight tests near the ground. During these flights the model was flown with the propeller shafts $1\frac{1}{2}$ to 2 feet above the ground. This height was maintained to the best of the power operator's ability. Actually the model dropped so low at times that the landing gear touched the ground and it rose so high at times that the lowest control surface was several feet above the ground. The flight behavior of the model was judged, however, only when the propeller shafts were about $1\frac{1}{2}$ to 2 feet above the ground. In all of these flights near the ground the pitch damper was used with a value of the response factor $d\delta_p/d\dot{\theta}$ of 0.6. The roll damper, however, was not used during any of these flights.

The test program also included vertical take-offs and landings. The roll damper was not used in these tests but the pitch damper was used for all take-offs and landings with a value of the response factor $d\delta_p/d\dot{\theta}$ of 0.6.

A few force tests were made to determine the effectiveness of the controls of the model. The main purpose of these tests was to provide a basis for evaluating the controls on future cascade-wing airplane designs by indicating the order of magnitude of the control moments required in flying an airplane of this general type. For the yaw-control-effectiveness tests the left and right yaw flaps were deflected differentially. All three of the right flaps were deflected together and all three left flaps were deflected together. For the roll-control tests, the pitch of the two outboard propellers was varied simultaneously from a trim setting of $12^{\circ}$; that is, the pitch of one propeller was increased while that of the other propeller was decreased. All these tests were made at a propeller speed of 5,500 revolutions per minute which corresponded closely to the speed for hovering flight.

Other force tests were made with the simplified test setups at various times before and after the present model was built and flown to determine the effectiveness of various wing configurations in turning the propeller slipstream and to determine the effectiveness of various flap configurations for use as controls. The results of these tests are presented in an appendix for the information of readers who might be interested in looking into the possibilities of other cascade-wing airplane configurations. These tests were not run in a systematic manner; therefore, the configurations and test conditions are described in the appendix along with the presentation of the test results.

## RESULTS AND DISCUSSION

The results of the present investigation are illustrated more graphically by motion pictures of flights of the model than is possible in a written presentation. For this reason a motion-picture film supplement to this paper has been prepared and is available on loan from the NACA Headquarters, Washington, D. C.

In general, it was almost impossible for the pilot to fly the model in the basic condition because of a violently unstable pitching oscillation. This oscillation could be stabilized with a pitch damper, however, and the behavior of the model was then fairly satisfactory in that take-offs and landings could be made and the model could be controlled fairly easily in hovering flight.

## Hovering Flight at Altitude

Pitching.- The flight tests showed that the model had a violently unstable pitching oscillation. This oscillation is shown in the time histories of the uncontrolled pitching motions presented in figure 6(a). These time histories show that the oscillation was a combination of pitching and longitudinal translation. The model seemed to have a very pronounced tendency to pitch nose-up if it moved forward or to pitch nose-down if it moved backward. It also had a tendency to move forward if it pitched nose-down or to move rearward if it pitched nose-up. These two force and moment variations are statically stabilizing. For example, if the model noses down, it starts to move forward and this forward movement causes it to pitch nose upward which tends to right the model and stop its forward motion. The phase relation of these motions, which appear stabilizing from static considerations, can be such as to produce an unstable oscillation if there is insufficient damping in pitch and insufficient damping of longitudinal translation. Evidently these damping factors were too small in proportion to the static stability parameters for the cascade-wing model.

In spite of this violently unstable oscillation the model could be controlled in pitch by careful use of the pitch control. This fact is illustrated in figure 6(b) by a time history of the pitching and longitudinal motions of the model in controlled flight. For this record the pilot was attempting to fly the model as smoothly as possible. The fact that the model was pitching through a rather large range of angles despite his efforts is evident from the figure. A full-scale airplane could probably be flown considerably more smoothly than the model because the angular velocities of the airplane would be much lower than those of the model and the pilot could sense the movements of the airplane and apply the proper amount of corrective control more exactly than was possible with the model. Whether or not its behavior would be considered tolerable cannot be definitely ascertained from the model tests, but the behavior of the model was considered unacceptable in comparison with that of other flying models.

The pitch damper was tried on the model as a means of improving its stability by increasing its damping in pitch. The tests over a wide range of values of the response parameter $d\delta_p/d\dot{\theta}$ indicated that the stability and controllability of the model improved progressively as the value of the response parameter was increased. Time histories of the model motions are presented for only two values of $d\delta_p/d\dot{\theta}$, 0.2 and 0.6. (See figs. 7 and 8.)

The value of $d\delta_p/d\dot{\theta}$ of 0.2 was chosen as the smallest value at which the pitching motions were considered easy to control. With this value of gearing the pilot considered the behavior of the model satisfactory even though the oscillation was still somewhat unstable as indicated by the time histories of the uncontrolled motions in figure 7(a). Comparison of the time histories for the controlled motions of figures 6(b) and 7(b) shows that the motions were somewhat smoother when the pitch damper was used. The factor that does not show up in these time histories is the ease of control. The model was so much easier to control with the pitch damper that the pilot was relaxed and at ease when flying with a damper response ratio of 0.2.

The value of $d\delta_p/d\dot{\theta}$ of 0.6 was chosen as the lowest value at which the pitching oscillation was completely stable. For this condition the model would fly for indefinite periods of time without the use of any manual control by the pilot. This result is illustrated in figure 8(a) by the time history of the uncontrolled pitching and longitudinal motions of the model. The model, of course, had no stability of position and consequently wandered around somewhat in response to disturbances such as the random air currents set up by recirculation of the slipstream within the building. No records were made specifically for illustrating the motions of the model in controlled flight with a value of $d\delta_p/d\dot{\theta}$ of 0.6 but two short records from flights made for other purposes have been read and plotted in figure 8(b). These flights were made at a later time than most of the tests and, as pointed out previously, the center of gravity was evidently in a different location as indicated by the difference in trim pitch angle. These records illustrate satisfactorily, however, the fact that the model can be flown very smoothly with this value of the damper response factor.

The results of the elevator-effectiveness force tests are shown in figure 9. These data are presented mainly to show the magnitude of the pitching moments required to fly the model. They may be useful in evaluating other types of pitch control surfaces for other cascade-wing configurations.

Rolling.- The uncontrolled rolling motions of the model appeared to be an aperiodic (not oscillatory) divergence involving lateral translation as well as rolling. These uncontrolled motions are illustrated in figure 10(a). It is difficult to tell whether such a motion is a true aperiodic divergence or simply the result of an out-of-trim rolling moment. It was the pilot's opinion, however, after many attempts to record the uncontrolled motion after trimming the model as carefully as possible, that this divergent motion actually indicated the instability of the model. The model was generally in fairly good trim since it was equipped with integrating-type trimmers which changed the trim a little in the direction that the control was deflected every time the pilot applied his flicker-type control. With this system the model becomes trimmed very accurately a short time after take-off.

The pilot could control the rolling motions of the model very easily despite the tendency toward a roll divergence. The controlled rolling motions presented in figure 10(b) are as smooth as those generally obtained with other free-flying models with flicker-type controls. The roll control provided by differential variation of the pitch of the outboard propellers appeared very powerful to the pilot. A quantitative indication of the effectiveness of this control can be obtained from the force-test data of figure 11.

There was a noticeable effect of the use of the yaw control on the rolling motions of the model. The use of right yaw control caused a rolling motion to the right and the use of left yaw control caused a rolling motion to the left. Since the yaw-control-effectiveness force tests of figure 12 show that the rolling moments produced by the yaw flaps were not in the correct direction to produce this rolling motion, it seems likely that the yawing velocity which resulted from applying yaw control was the actual cause of the rolling due to yaw control which was noticed in the flight tests. In any event, this cross-coupling effect was not very troublesome to the roll pilot and he could fly the model steadily in roll despite the fact that the yaw pilot applied the yaw control frequently.

In the controlled flights it appeared that the damping in roll was low since the final rolling velocity produced by the roll control appeared high although the initial roll response seemed normal. In order to determine whether an increase in damping in roll would improve the stability and controllability, a roll damper was installed in the model. With this roll damper operating at a value of the response factor $d\beta/d\dot{\phi}$ of 0.4, the uncontrolled rolling motions of the model appeared much less divergent as is indicated by comparison of the time histories of figure 13(a) with those of figure 10(a). Controlled flight was considerably easier with the roll damper than without it and the model could be flown much more smoothly as indicated by comparison of figure 13(b) with figure 10(b). The addition of a roll damper to an airplane of this type, which did not already have the roll damper or its main elements for some other purpose, would probably not be warranted for hovering flight since the behavior of the model seemed satisfactory without the damper.

It is probably worthy of note that in some preliminary flights a different roll control system was used and that this system did not provide sufficiently powerful control to permit sustained flight. This roll control system made use of the wing flaps but did not make use of the propeller pitch. The flaps on the two upper wings (the flaps used for yaw control on the final configuration) were deflected toward each other to partially block the passage between these wings and thereby reduce the lift on either the left or right wings to produce a rolling moment.

Yawing.- The observations of the yaw pilot indicated that the yawing motions of the model were sufficiently damped and very easy to control. Of course, there was no stability of yaw position since there was no static restoring moment in yaw. Continuous use of yaw control was therefore required to prevent yawing as a result of the random air currents caused by recirculation of the slipstream in the building. It is important to maintain a constant heading in flying the model since the model must be properly oriented with respect to the remote pilots in order for them to control the model effectively. There was no noticeable yawing caused by rolling or the roll control. Evidently the yawing moment produced by the roll control shown by the force-test results of figure 11 was too small to cause any noticeable yawing or perhaps there was a yawing moment caused by rolling velocity which tended to oppose the yawing moment caused by the roll control.

The results of the yaw-control-effectiveness force tests are shown in figure 12. These data may be useful in evaluating other types of yaw control surfaces for other cascade-wing configurations.

Vertical motions.- The vertical motions of the model were fairly difficult to control. Part of this difficulty was caused by the lag in the power control system in which it was necessary to accelerate or decelerate several heavy-duty components of the motor-generator power-supply unit before the model motor speed changes. The vertical motions of the cascade-wing model, however, were more difficult to control than those of models with the propeller shaft axis vertical when operated from this motor-generator set. Evidently the cascade-wing model has less damping of the vertical motions than a model with the propeller-shaft axis vertical, which is known to have considerable damping because of the pronounced inverse variation of the thrust of a propeller with axial velocity.

## Hovering Flight Near the Ground

The model appeared to have as good stability and control characteristics when hovering near the ground as when hovering at a considerable height above the ground. Only a very limited amount of flying was done near the ground, however. As pointed out previously, all of the flights near the ground were made with the pitch damper operating with a gearing ratio $d\delta_p/d\dot{\theta}$ of 0.6 which was found to make the model completely stable in pitch when hovering well above the ground. It was necessary to fly the model continuously when hovering near the ground because any small angular motions tended to make the model lose altitude and touch the ground. The stability of the model could not be studied, therefore, by observing the uncontrolled motions. From the general ease of maintaining steady flight, however, it appeared that the stability when the model was hovering near the ground was as good as when hovering at altitude. There was no noticeable adverse effect of ground proximity on the effectiveness of any of the controls even though the pitch flap in particular was very close to the ground (about half a propeller diameter) during the hovering flights near the ground. A time history of the longitudinal motions of the model when hovering near the ground is given in figure 14. Comparison of the time history of this figure with that of figure 8(b) shows the similarity of general steadiness and frequency of control used. The records presented in figure 14, as well as those of figure 8(b), were obtained at a later time and with a different center of gravity from that for the rest of the flight tests.

There was a slight tendency for the model to move forward as it neared the ground. It was necessary therefore to increase the angle of pitch of the model by the use of up-elevator trim as the model neared the ground. This change in pitch attitude can be seen by comparison of figure 14 with figure 8(b). There was also a slight increase in propeller speed required as the model neared the ground. This result was obtained only from the observations of the power operator since no quantitative power data were obtained.

## Take-Offs and Landings

Take-offs and landings were easy to perform. Time histories of four take-offs and four landings are shown in figures 15 and 16. Two each of these take-off and landing records show the pitching motion and two show the rolling motion. The pitch and roll records do not show the same flights since only one camera was used during the tests.

When trimmed for hovering flight well above the ground, the model had a tendency to move forward as it took off or as it neared the ground on landing. This is the same effect noted in the preceding section of this paper. This forward motion could be eliminated for normally fast take-offs by use of the proper ground angle. In any event, this tendency to move forward on take-offs and landings would probably be less troublesome to the pilot of a full-scale airplane than to the pilot of the model because he would have a proportional elevator control system rather than the flicker control system used on the model.

## SUMMARY OF RESULTS

The following results were obtained from take-off, landing, and hovering flight tests of a cascade-wing vertically rising airplane model in still air:

1. It was almost impossible for the pilot to fly the model without the use of artificial damping in pitch because of a violently unstable pitching oscillation.

2. This pitching oscillation could be stabilized by the use of a rate-sensitive artificial damper which also made the pitching motions easy to control.

3. The rolling motion was slightly divergent but was easy to control.

4. The use of a rate-sensitive artificial stabilizing device in roll made this rolling motion about neutrally stable.

5. The model apparently had considerable damping in yaw and the yawing motions could be controlled easily.

6. Vertical take-offs and landings could be performed satisfactorily.

7. The only unusual behavior noted when the model was flying near the ground was a slight tendency to pitch nose down and to move forward when trimmed for hovering flight well above the ground.

8. Some difficulty was experienced in controlling the vertical motions of the model, apparently because there was very little damping of these motions.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 18, 1954.

# APPENDIX

## EXPLORATORY FORCE TESTS WITH SIMPLIFIED MODELS

The exploratory force tests with simplified models were made to obtain some preliminary indication of the relative efficiency of variou wing configurations in turning the propeller slipstream and the effectiveness of various vanes or flaps for use as controls. The data from these force tests are presented only to provide some general informatio in a little-explored field. Some of these tests were run prior to the design of the present hovering model to find a reasonably simple config ration for a hovering model with which reasonable control moments could be obtained. The other tests were made as a preliminary step in the design of a model for tests in the transition range of flight between hovering and normal forward flight. In these latter tests the aim was to find a configuration which might be reasonably efficient in both hovering and normal forward flight and with which adequate control could be obtained.

The force-test data will be grouped as performance data and control data for simplicity of presentation. They are presented in dimensional form since the nondimensional form in which the data would be useful wil depend on the use to which the data are put.

### Performance Tests

The results of the tests to determine the efficiency of various arrangements of wings in turning the propeller slipstream are summarized in table I. The configurations tested are indicated by the sketches in this table which show the airfoil and the arrangement of the wings. In all of these sketches the propeller slipstream approaches from the left. The diameter of the propeller was 10.5 inches for most of the setups and the height of the wing system was the same as the diameter of the theoretical slipstream (0.7 of the propeller diameter). All of the wings except those for configurations 1 and 3 were made of curved or bent plates of sheet metal. The airfoil section for configurations 1 and 3 was that of the same wind-tunnel turning vane used on the flying model. The efficiency of the wing systems for hovering flight is indicated by the factor $W/T$, the ratio of the weight that can be lifted in hovering flight to the propeller thrust. A second factor of primary interest is the pitch angle $\theta$ required for hovering flight; that is, the angle at which the horizontal component of the lift and drag of the wing system is equal to the horizontal component of the thrust. This angle is also approximately the ground angle required for vertical take-off.

The results of tests to determine the effect of the distance of the propeller ahead of the approximate center-of-gravity position of a cascade wing and the effect of tilting the wing system relative to the propeller are presented in figure 17. Distance is given in propeller diameters. The figure also indicates the thrust of the propeller for comparison with the lift and drag of the wing. These tests were run with a larger model (propeller diameter 22 inches) than those used in obtaining the data presented in table I so the two sets of data are not directly comparable because of possible scale effects.

## Control Tests

The results of the control-effectiveness tests are presented in figures 18 and 19. The data for figure 18 were obtained with models with a 22-inch-diameter propeller, whereas those of figure 19 were obtained with smaller models with a 10.5-inch-diameter propeller. The thrust of the 22-inch propeller was about 9.5 pounds, whereas that of the 10.5-inch propeller was about 12.5 pounds.

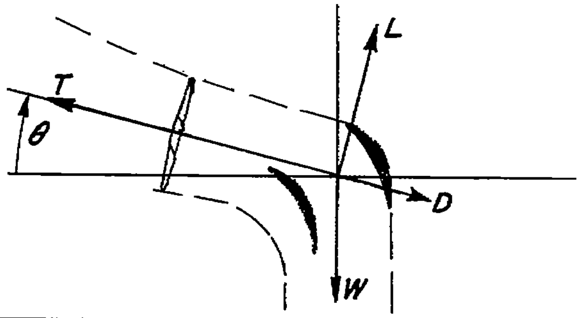
The airfoil of the models used with the 22-inch propeller (fig. 18) was that of the wind-tunnel turning vane used on the flying model; whereas the wings of the models with the 10.5-inch propeller (fig. 19) were made of bent or curved plates of sheet metal.

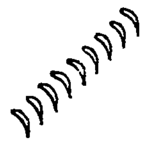
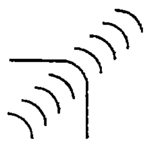
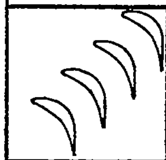
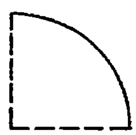
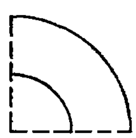
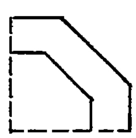
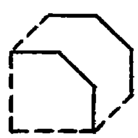
The effect of varying the angles of various combinations of vanes of a cascade of small wings is shown in figures 18(a) to 18(d). In figures 18(a) and 18(b), all the vanes above the center of gravity or below the center of gravity were deflected simultaneously. The effect of varying the deflection of various flaps or combinations of flaps on a cascade of four larger wings is presented in figures 18(e) to 18(g); the effect of varying the deflection of the flaps on a biplane wing is shown in figure 19(a); and the effect of varying the deflection of a flap on a large wing used in conjunction with a number of small wings is shown in figure 19(b).

## REFERENCE

1. Collar, A. R.: Some Experiments With Cascades of Aerofoils. R. & M. No. 1768, British A.R.C., Dec. 1936.

Table I.– Performance data for simplified-model tests




| Configuration | | θ, deg | L/T | D/T | W/T |
|---|---|---|---|---|---|
|  | 1 | 7.5 | 0.92 | 0.88 | 0.92 |
|  | 2 | 12.5 | .83 | .82 | .85 |
|  | 3 | 5.0 | .85 | .93 | .85 |
|  | 4 | 38.9 | .54 | .56 | .69 |
| | 4P* | 28.2 | .68 | .64 | .77 |
|  | 5 | 27.7 | .66 | .65 | .75 |
| | 5P | 21.2 | .75 | .71 | .81 |
|  | 6 | 21.3 | .66 | .74 | .71 |
| | 6P | 11.9 | .81 | .83 | .82 |
|  | 7 | 20.2 | .65 | .76 | .69 |
| | 7P | 13.6 | .78 | .81 | .80 |

* P designates end plates which are shown dotted in the sketches.

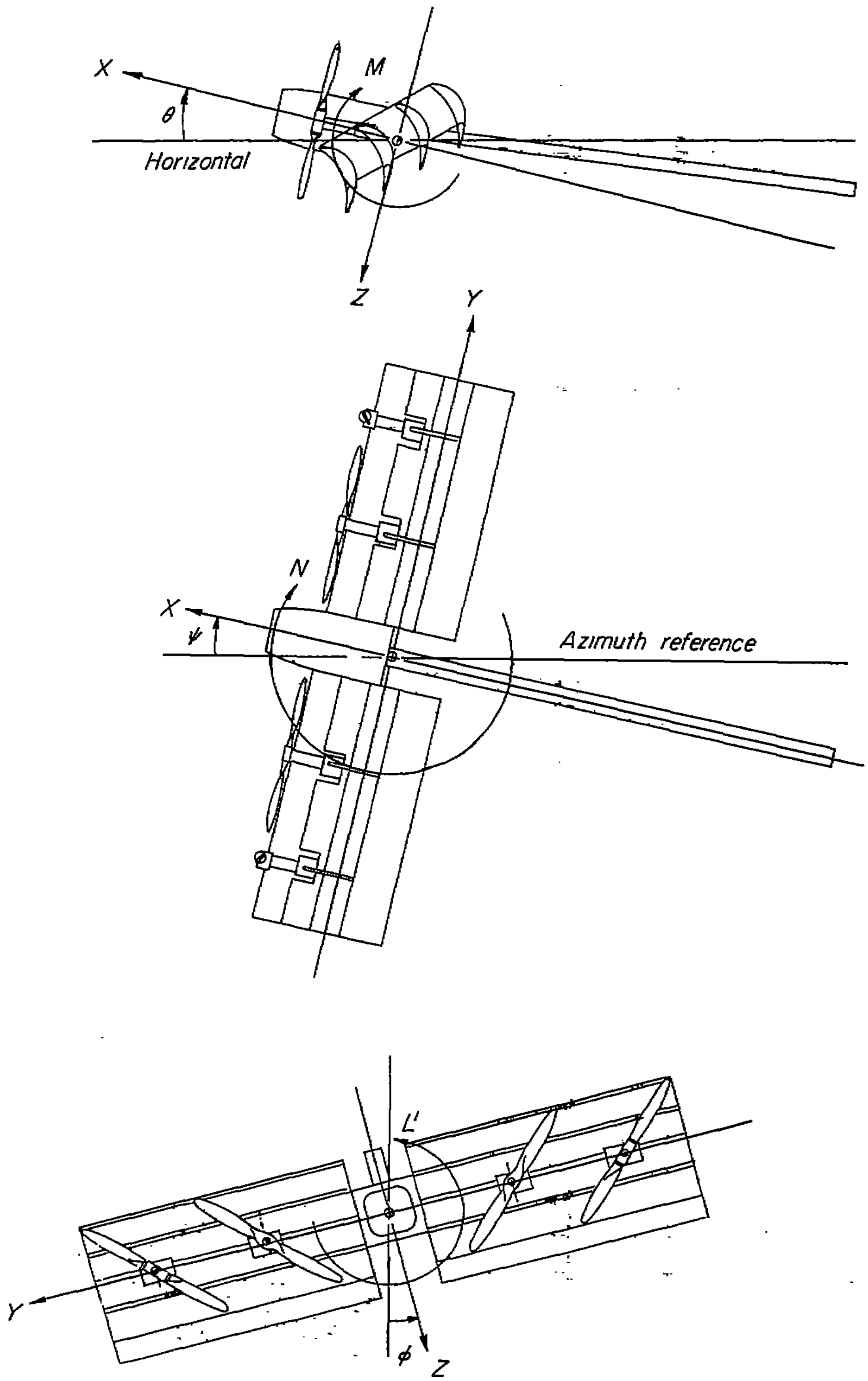
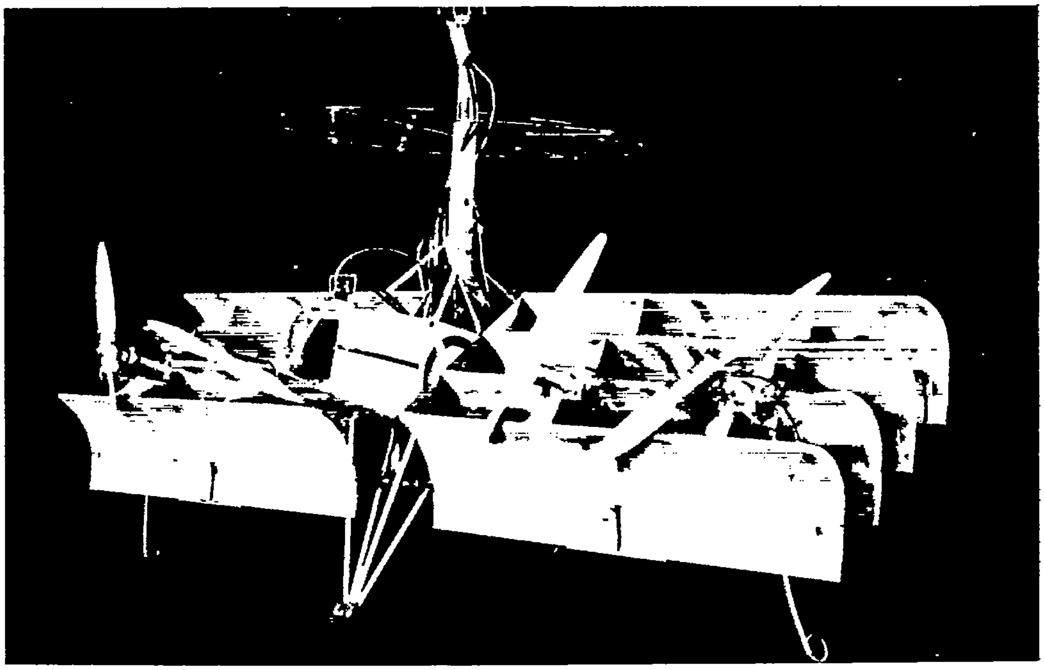
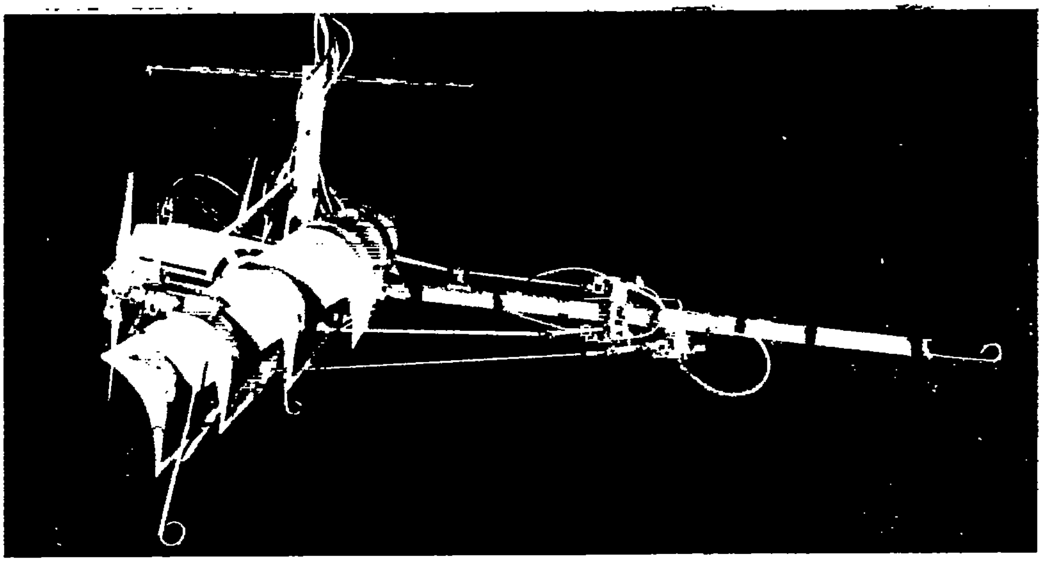



Figure 1.- The body system of axes. Arrows indicate positive directions of forces, moments, and angular displacements.



L-78097

(a) Three-quarter front view.



L-78099

(b) Side view.

Figure 2.- Photographs of the cascade-wing model.

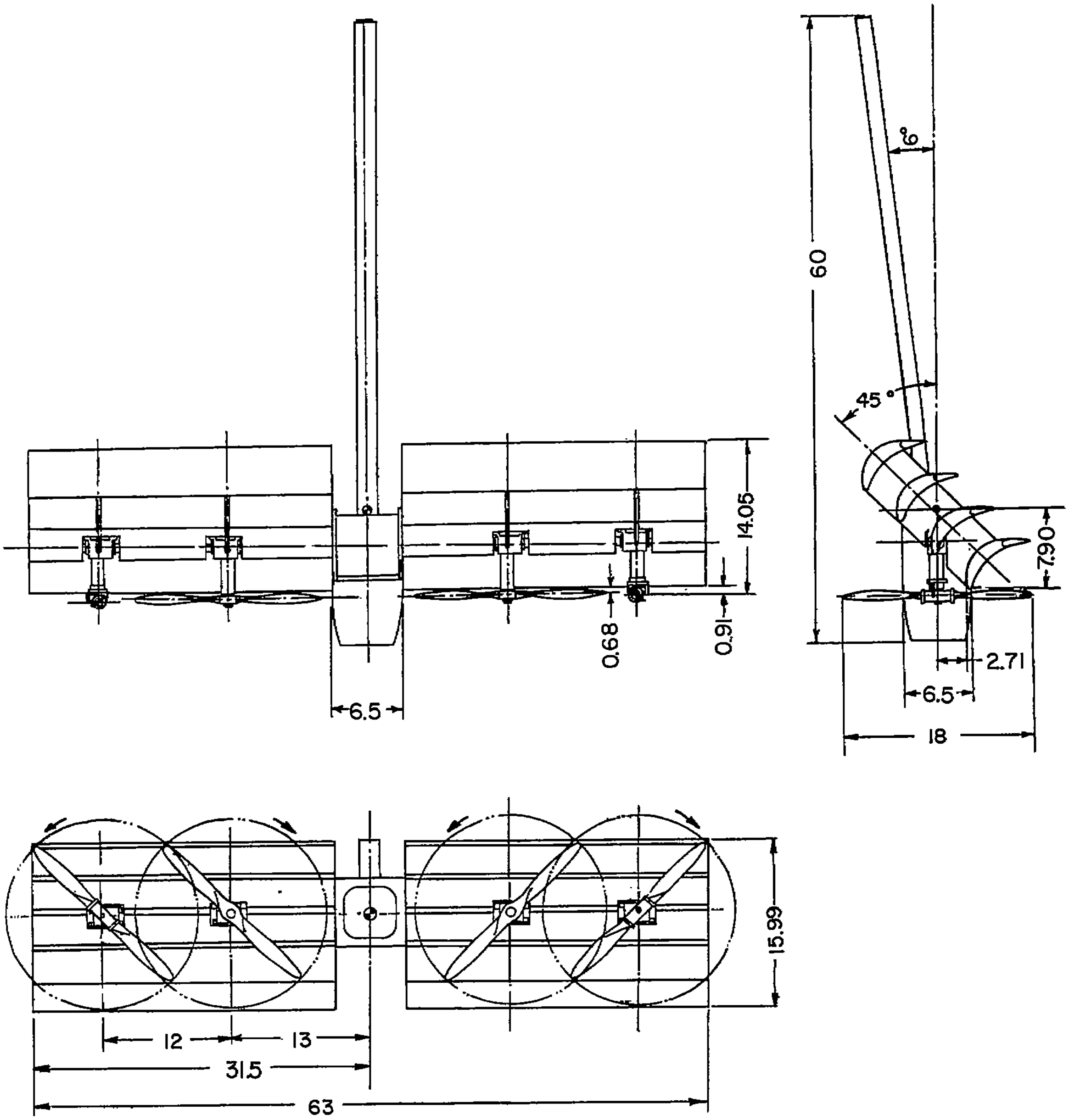



Figure 3.- Three-view sketch of cascade-wing model. All dimensions are in inches.

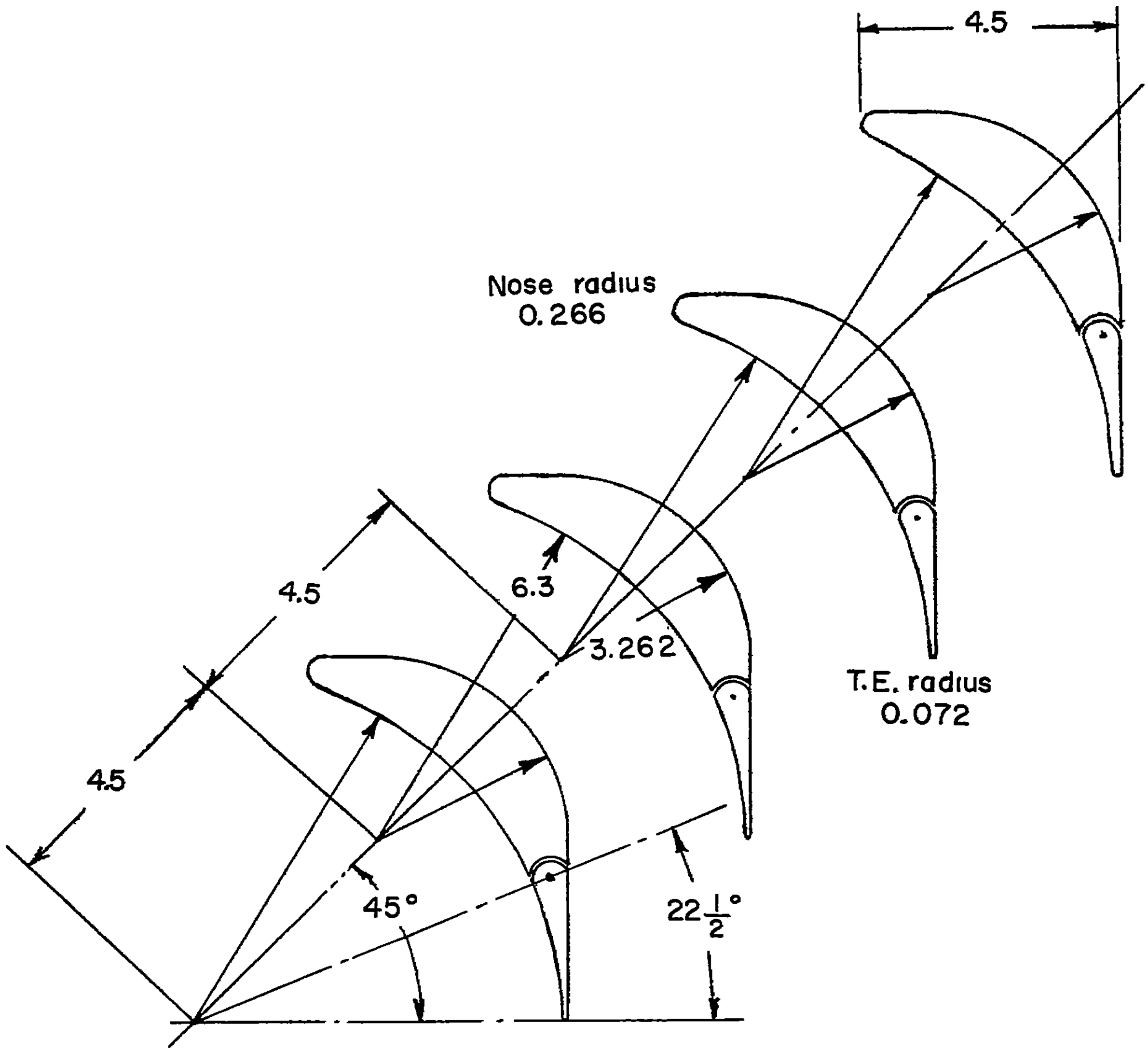
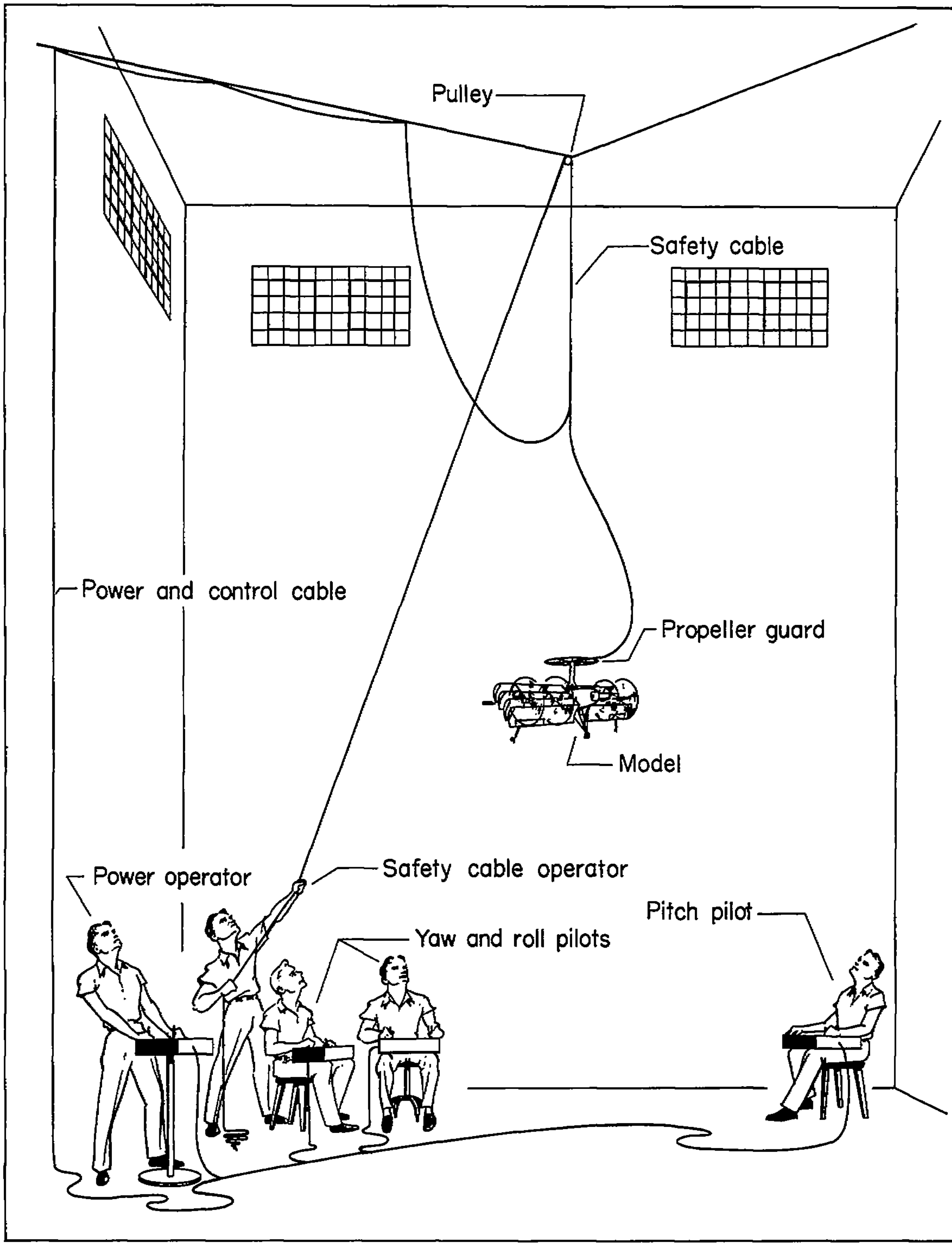
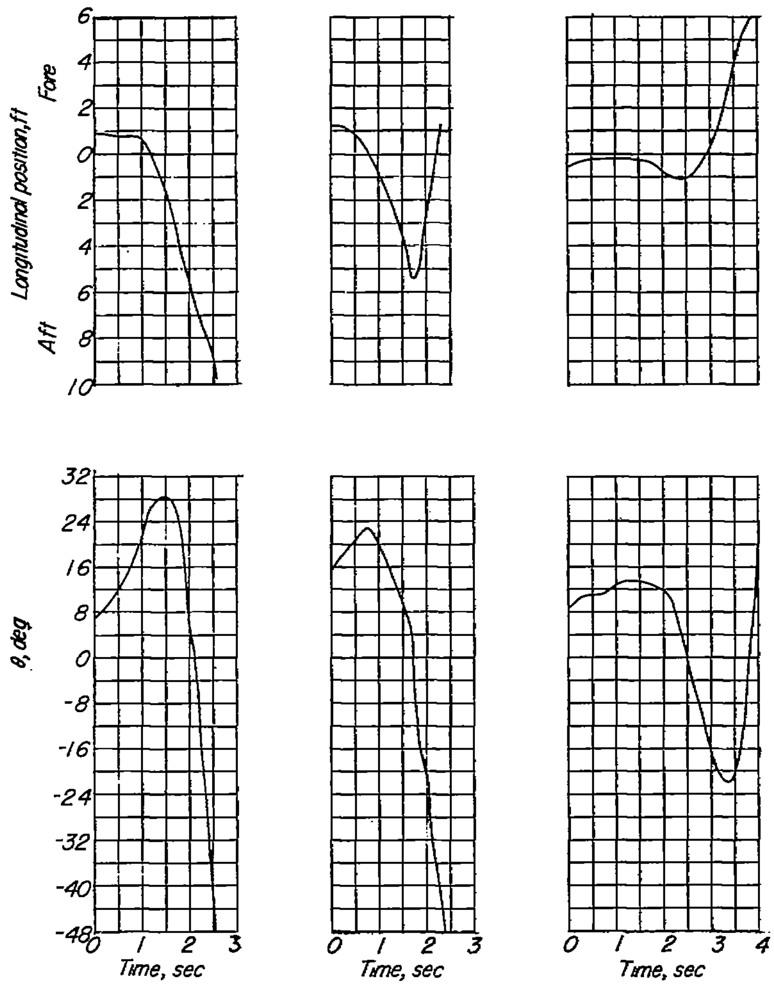



Figure 4.- Details of wing arrangement and airfoil section. All four wings identical. All dimensions are in inches.

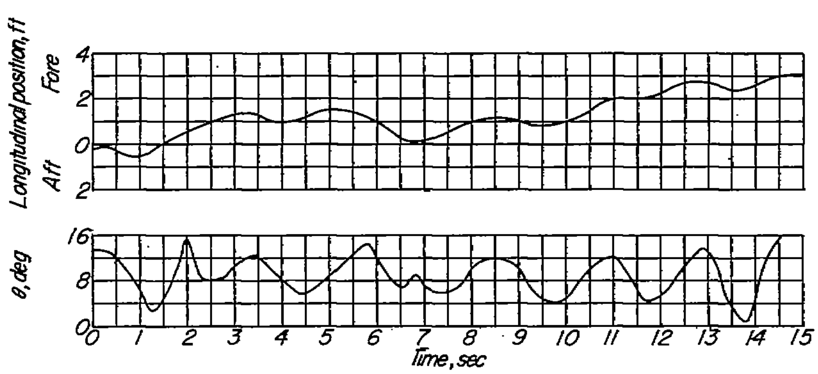



L-83333

Figure 5.- Test setups used in flight testing hovering models.

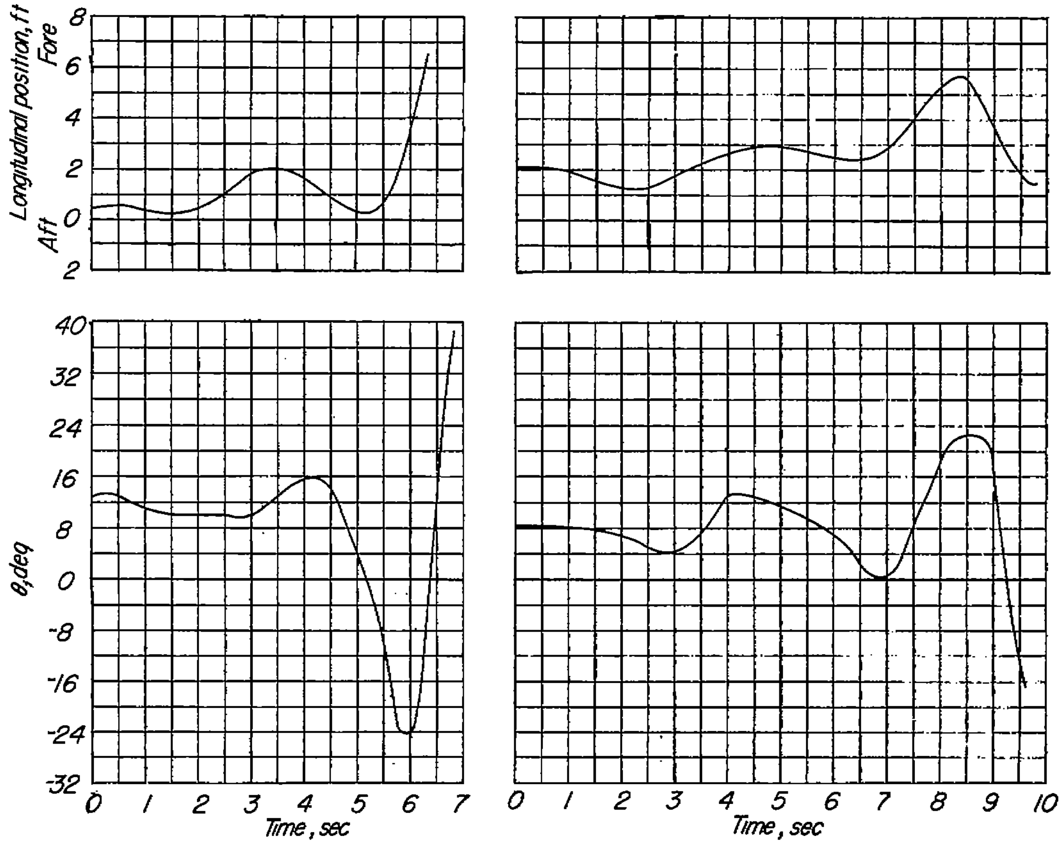



(a) Uncontrolled flight.

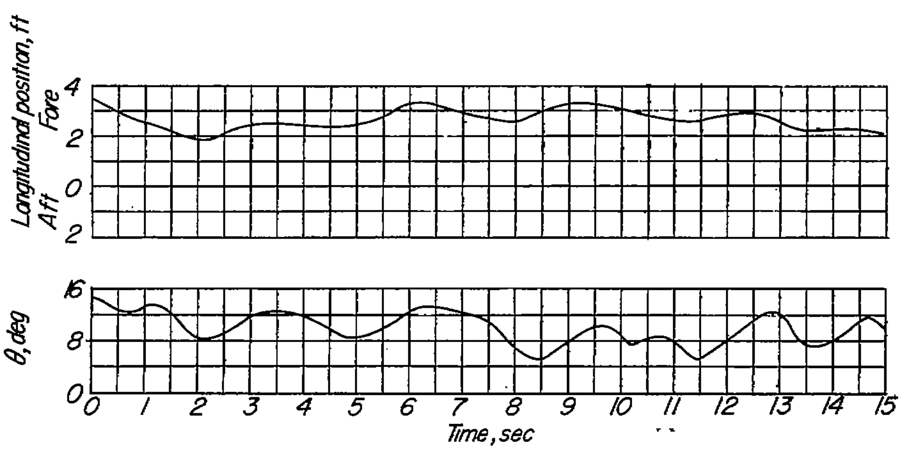



(b) Controlled flight.

Figure 6.- Pitching motions of the model without pitch damper.

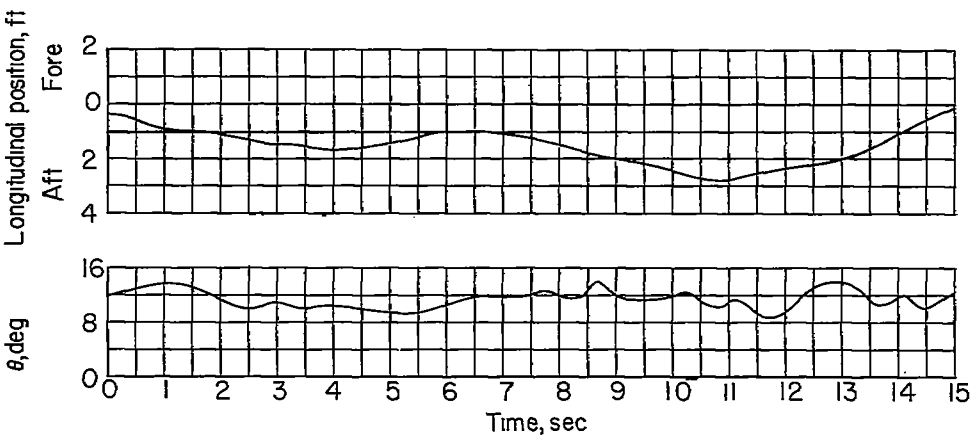



(a) Uncontrolled flight.

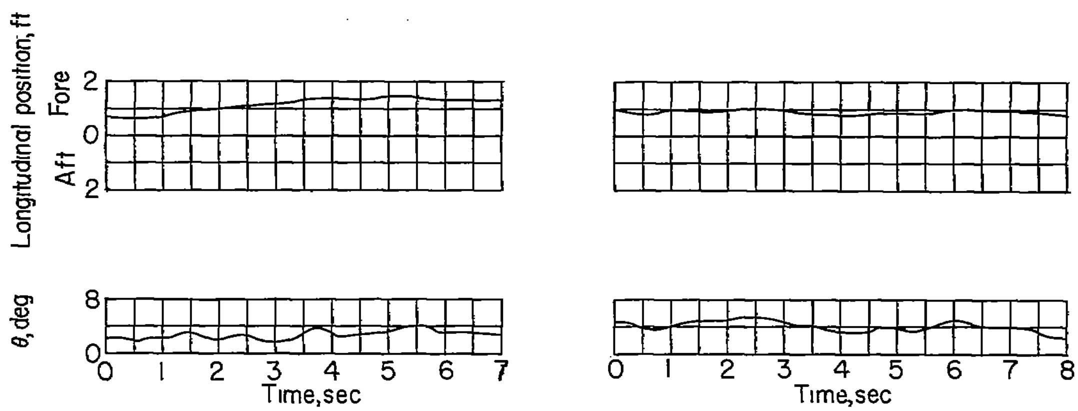



(b) Controlled flight.

Figure 7.- Pitching motions of the model with pitch damper. $\frac{d\delta_p}{d\dot{\theta}} = 0.2.$




(a) Uncontrolled flight.




(b) Controlled flight.

Figure 8.- Pitching motions of the model with pitch damper. $\frac{d\delta_p}{d\dot{\theta}} = 0.6$.

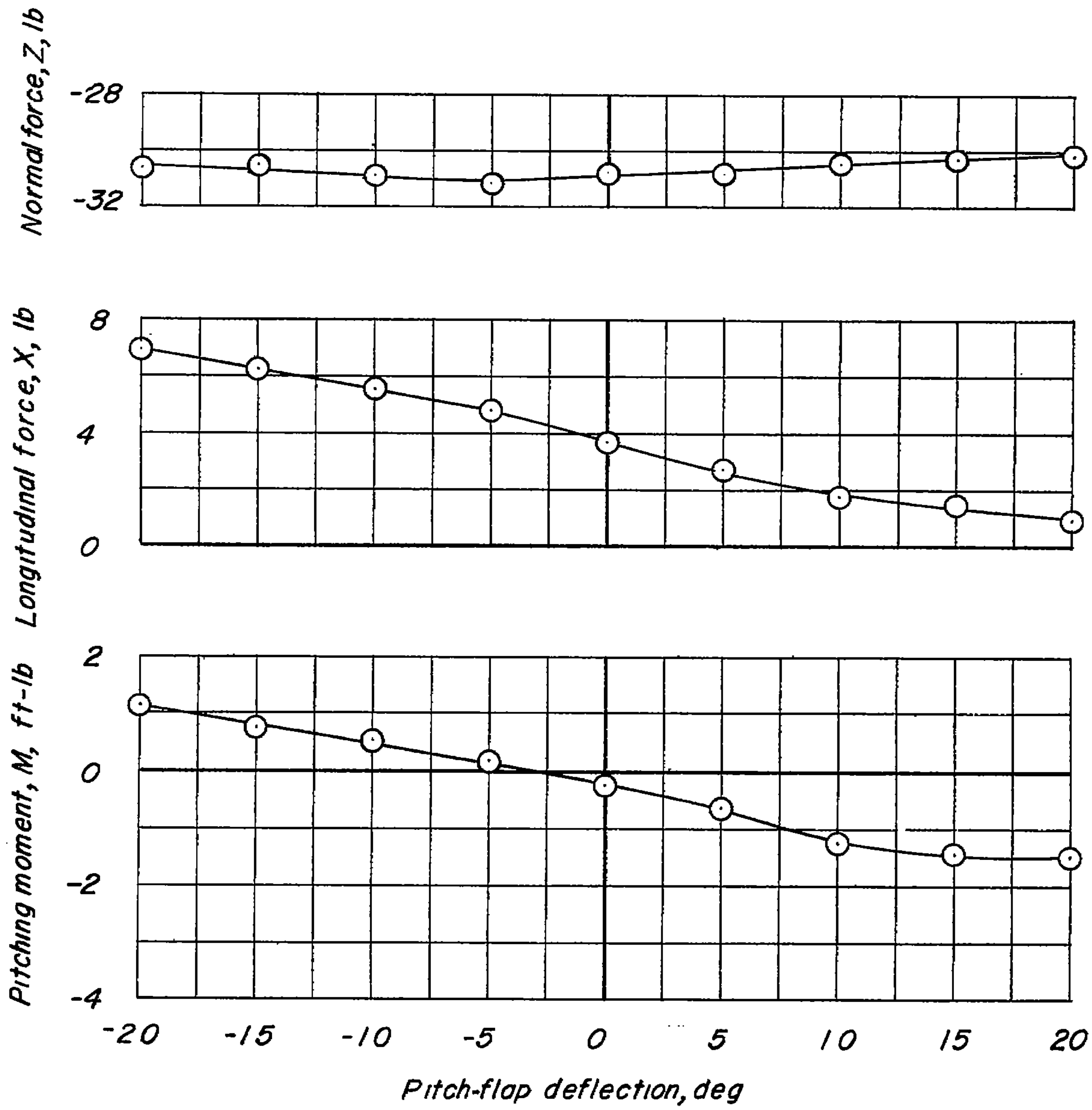
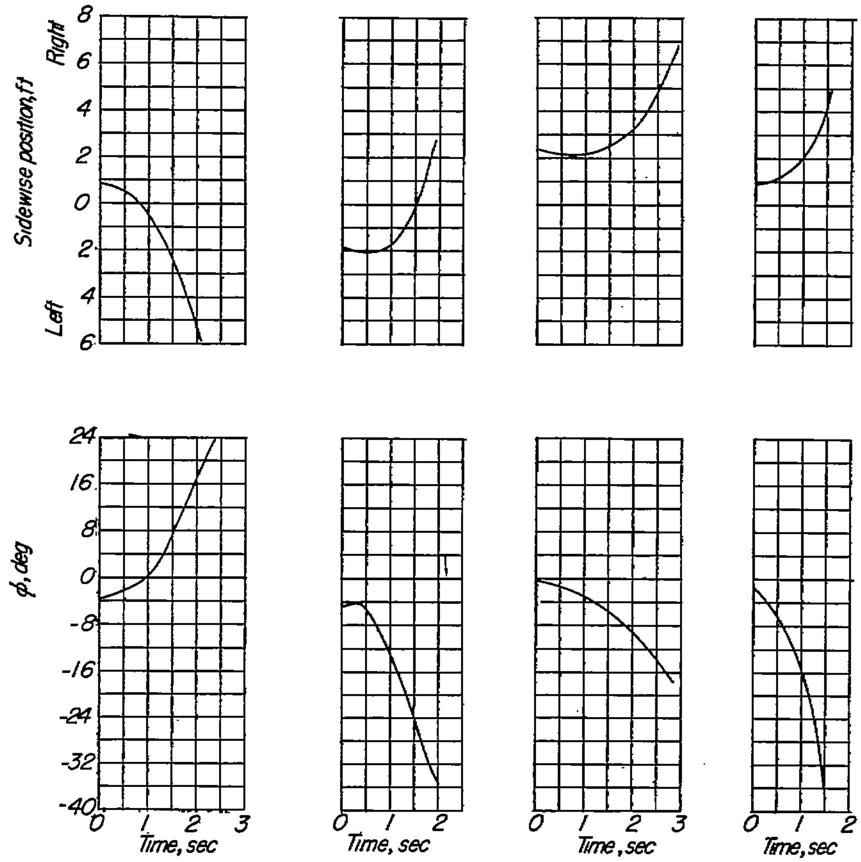
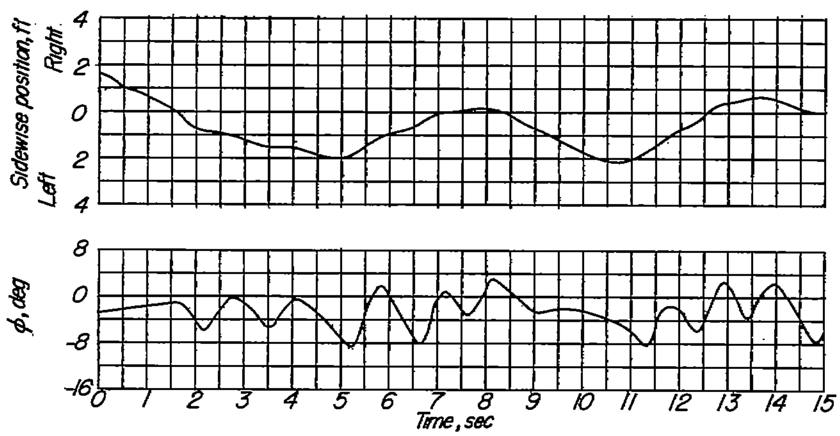



Figure 9.- Pitch control effectiveness from force tests of model.




(a) Uncontrolled flight.




(b) Controlled flight.

Figure 10.- Rolling motions of the model without roll damper.

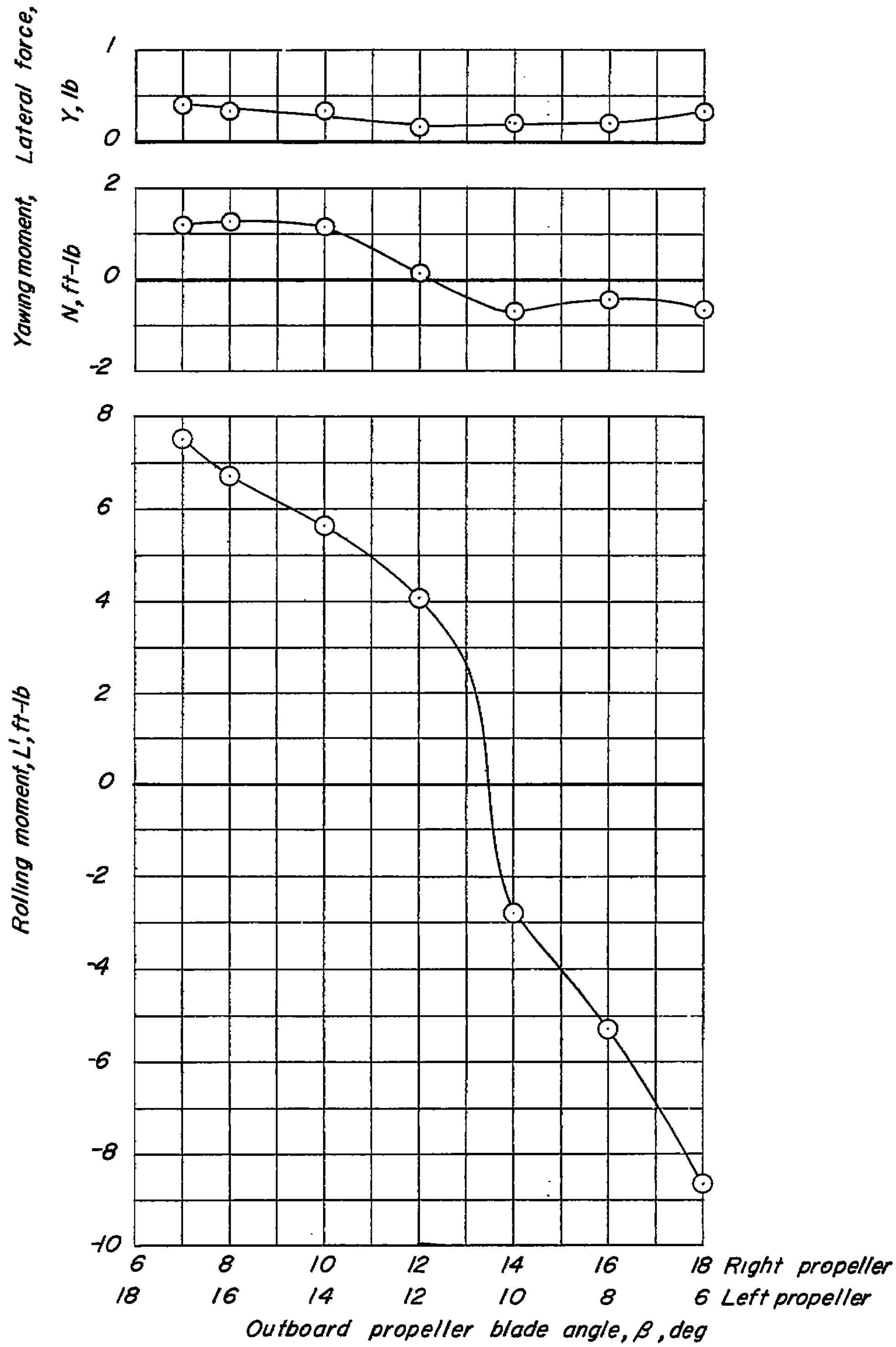



Figure 11.- Roll control effectiveness from force tests of the flying model. Right and left propellers deflected simultaneously.

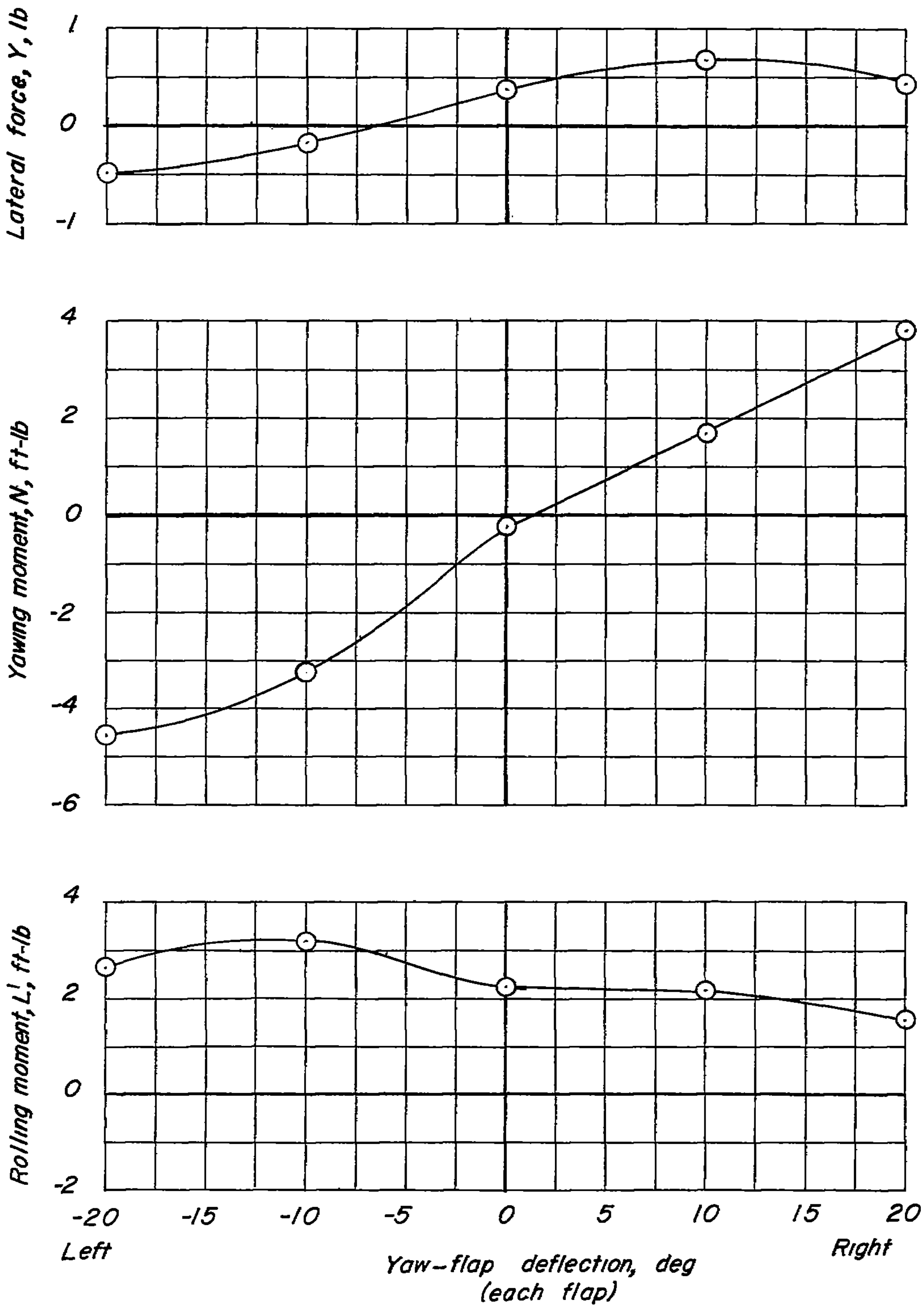
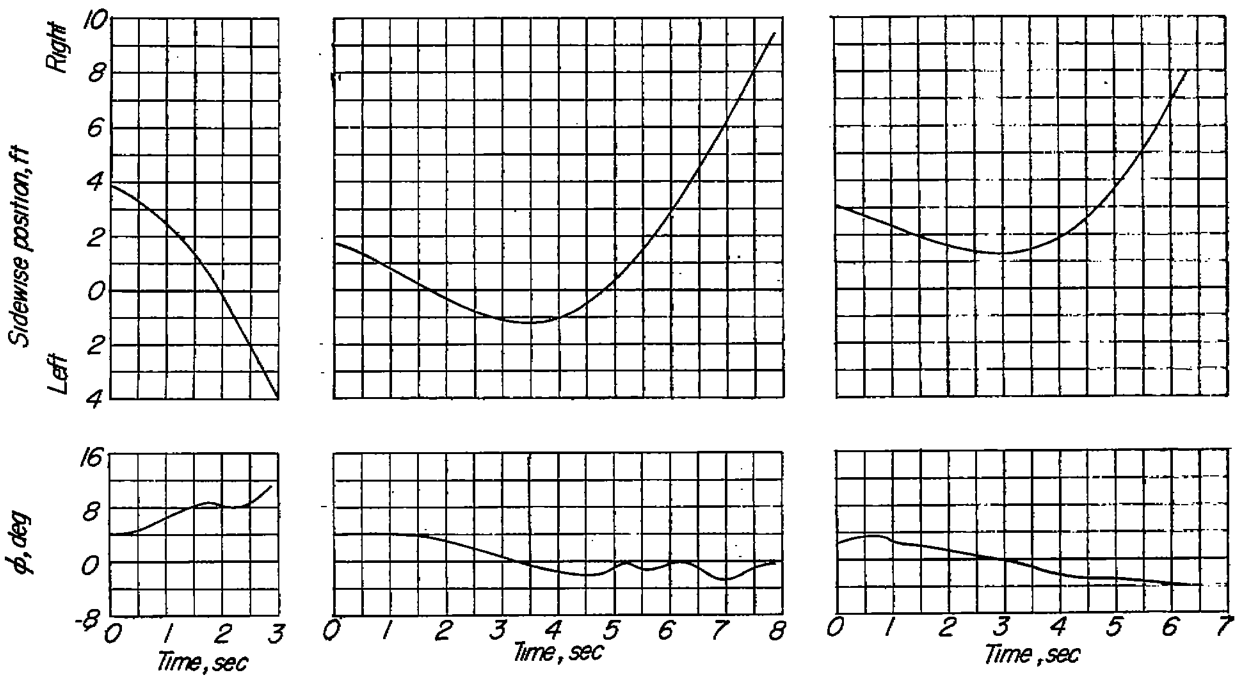
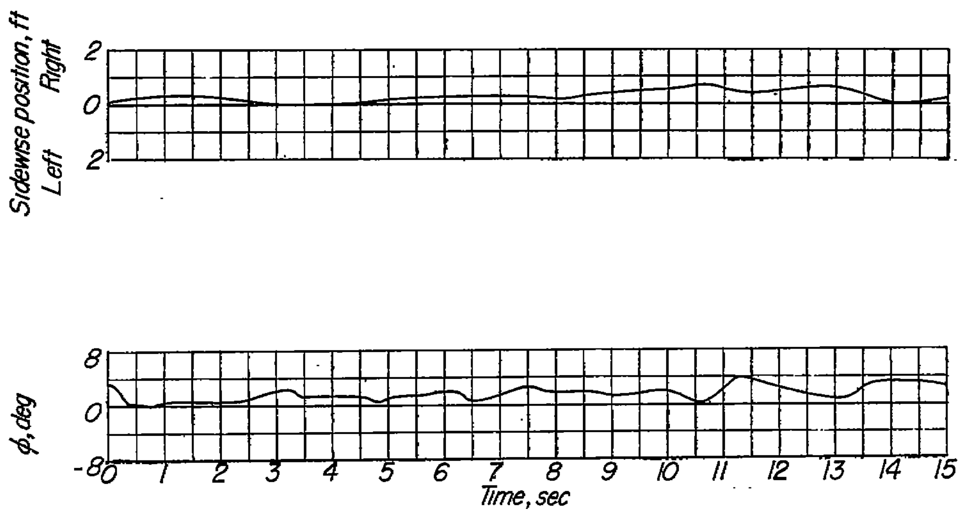



Figure 12.- Yaw control effectiveness from force tests of the flying model. For right yaw-flap deflection, the three flaps on the right wing deflect forward and the three flaps on the left wing deflect backward.




(a) Uncontrolled flight.




(b) Controlled flight.

Figure 13.- Rolling motions of the model with roll damper. $\frac{d\beta}{d\dot{\phi}} = 0.4$.

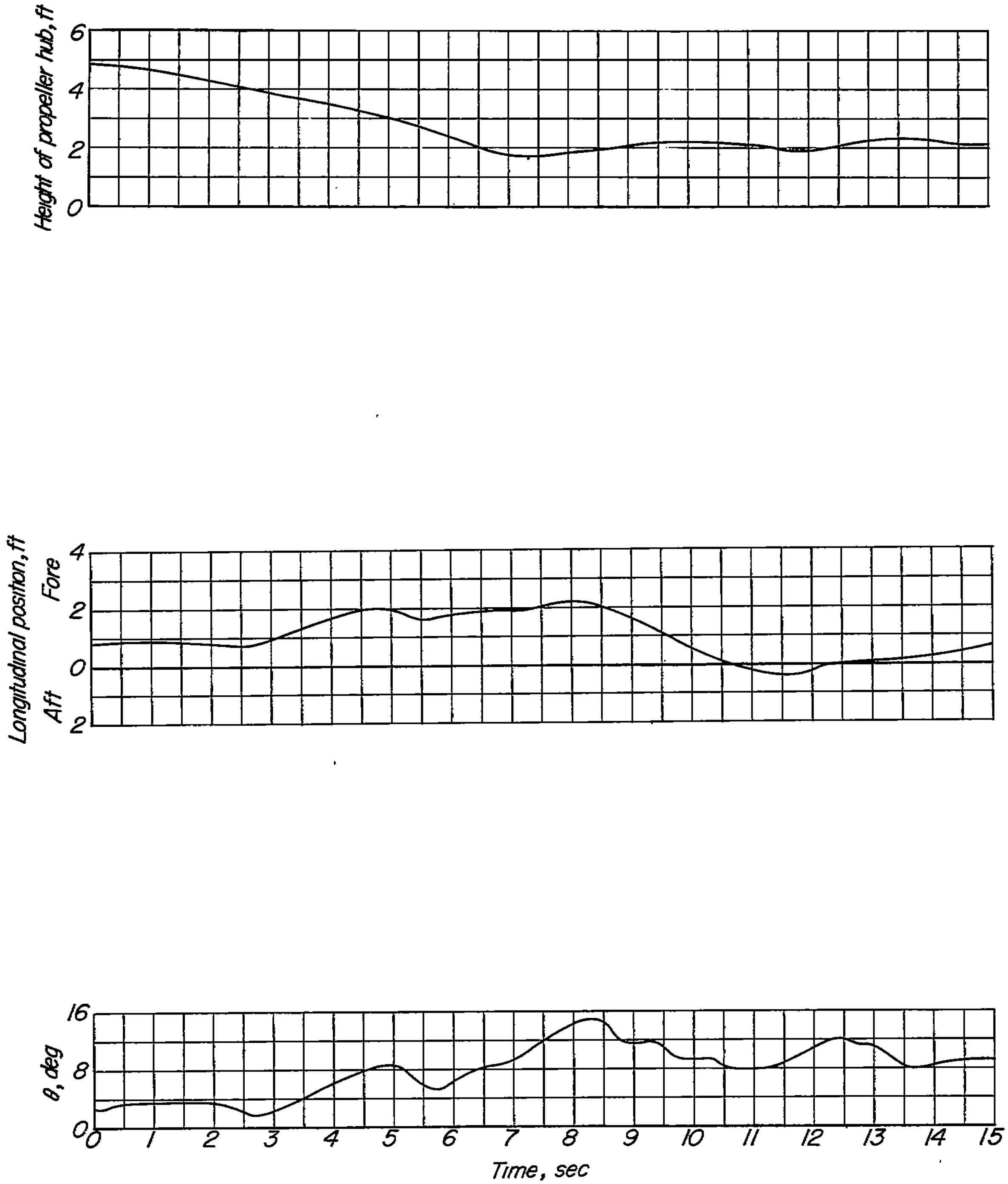
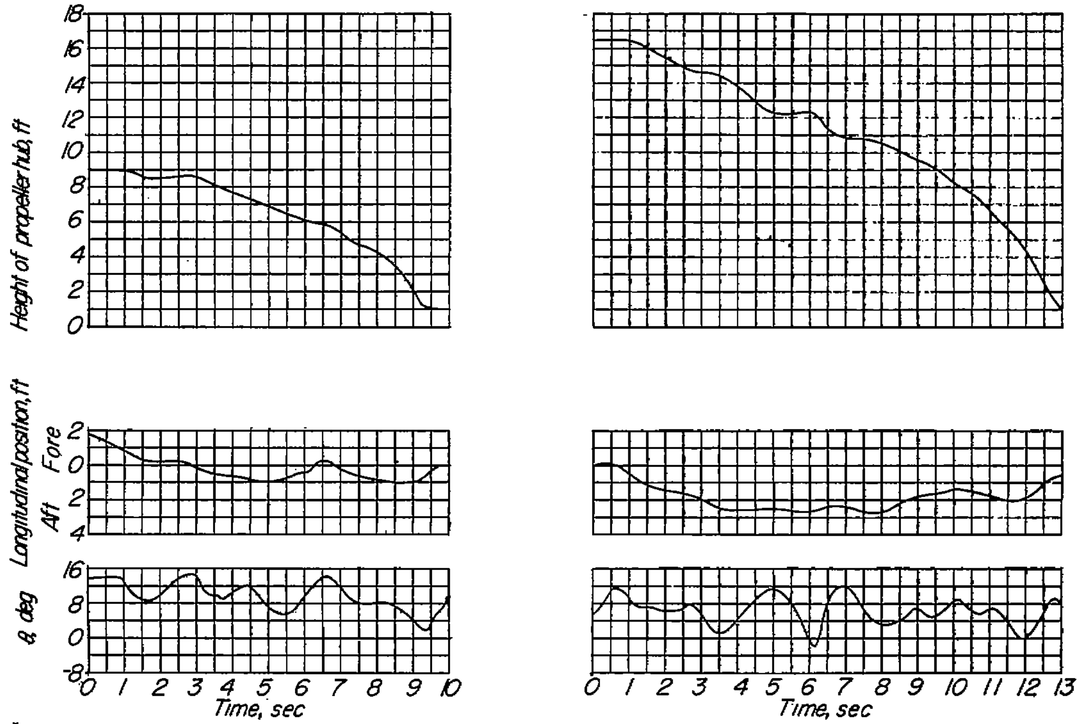
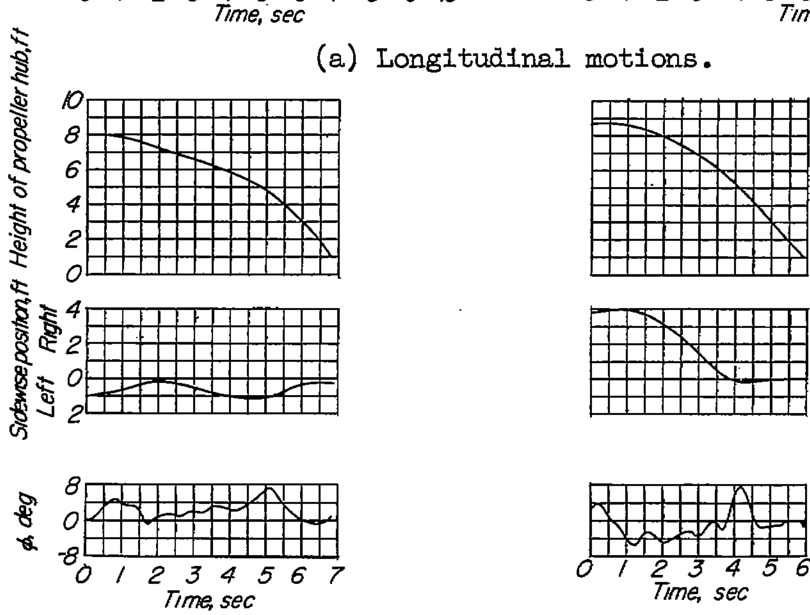



Figure 14.- Controlled flight near the ground with pitch damper. $\frac{d\delta_p}{d\dot{\theta}} = 0.6$.

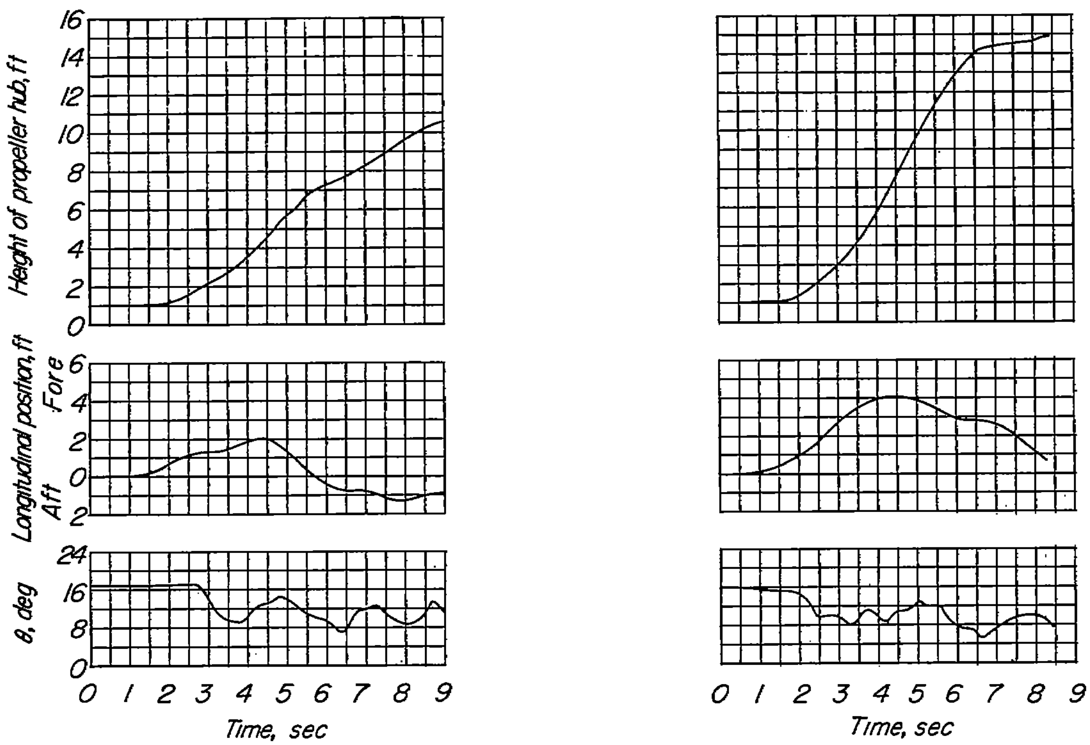



(a) Longitudinal motions.

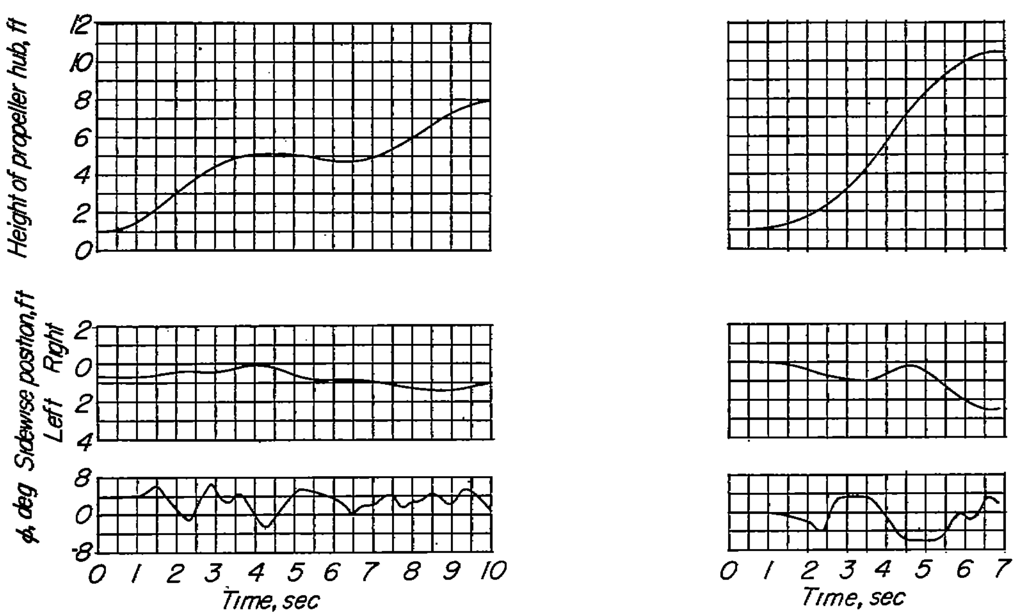



(b) Lateral motions.

Figure 15.- Time histories of landings. (All records terminated at time of touchdown.)




(a) Longitudinal motions.




(b) Lateral motions.

Figure 16.- Time histories of take-offs.

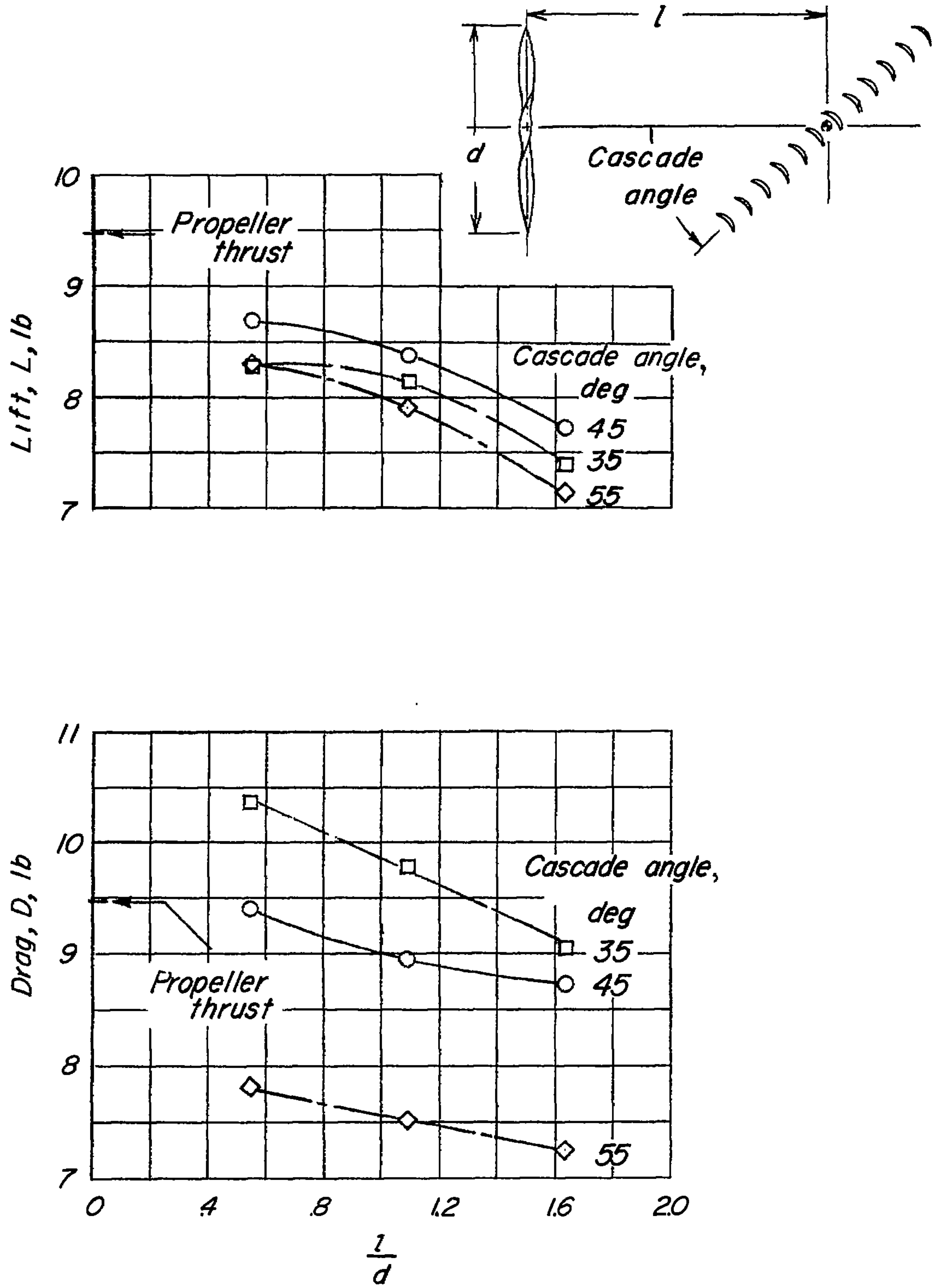
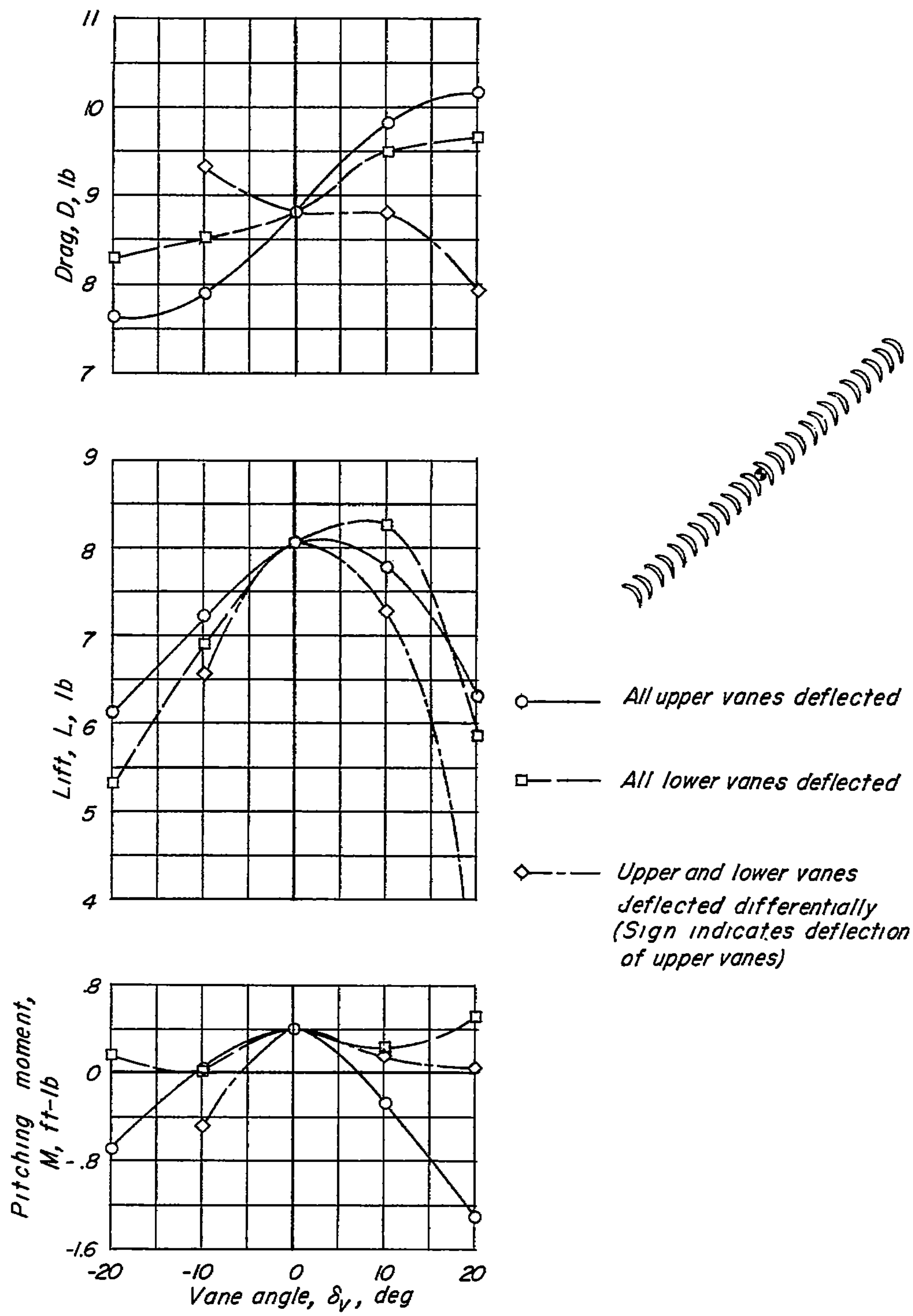
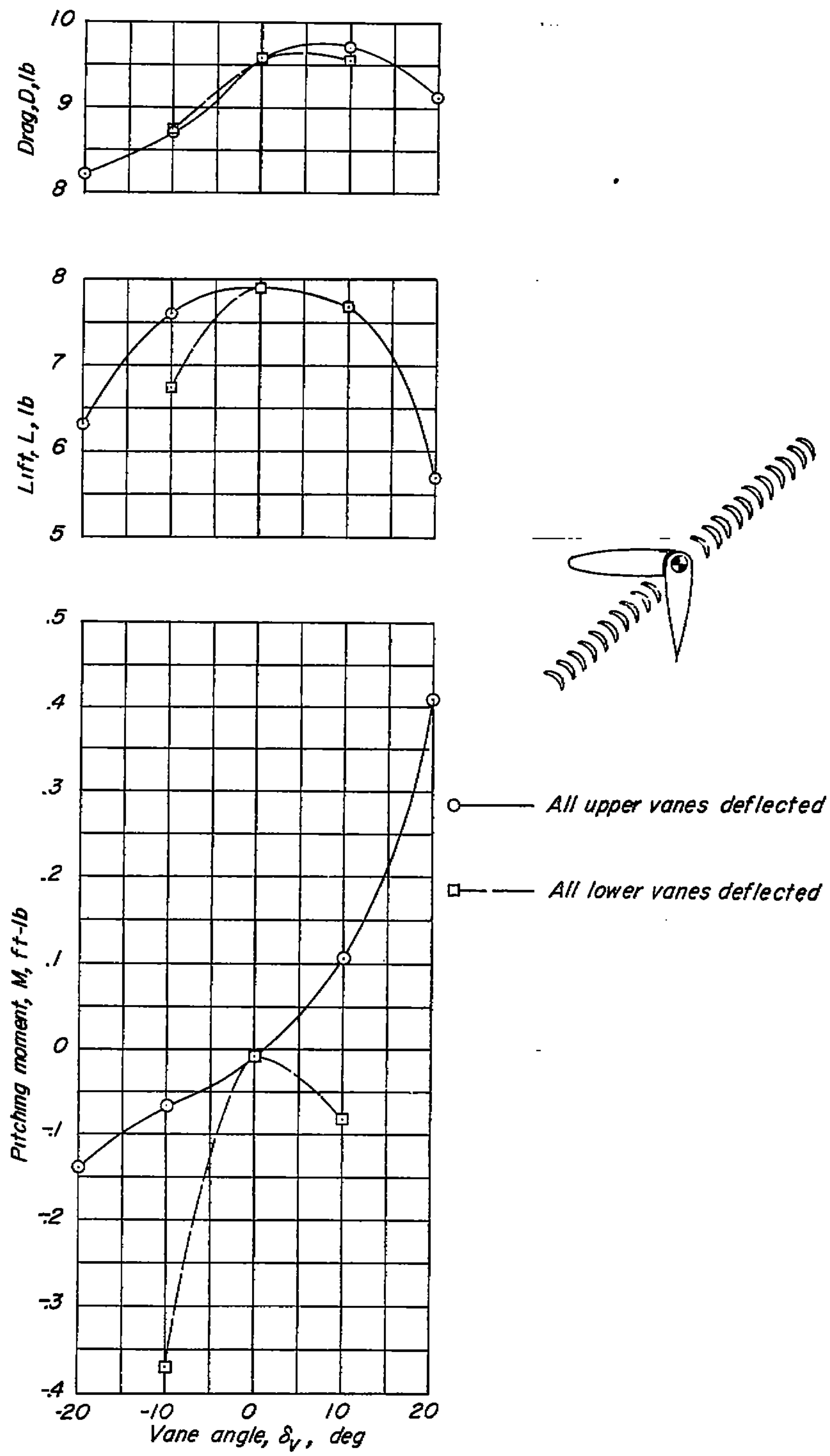



Figure 17.- Effect of propeller distance and cascade angle on performance of a cascade-airfoil configuration.



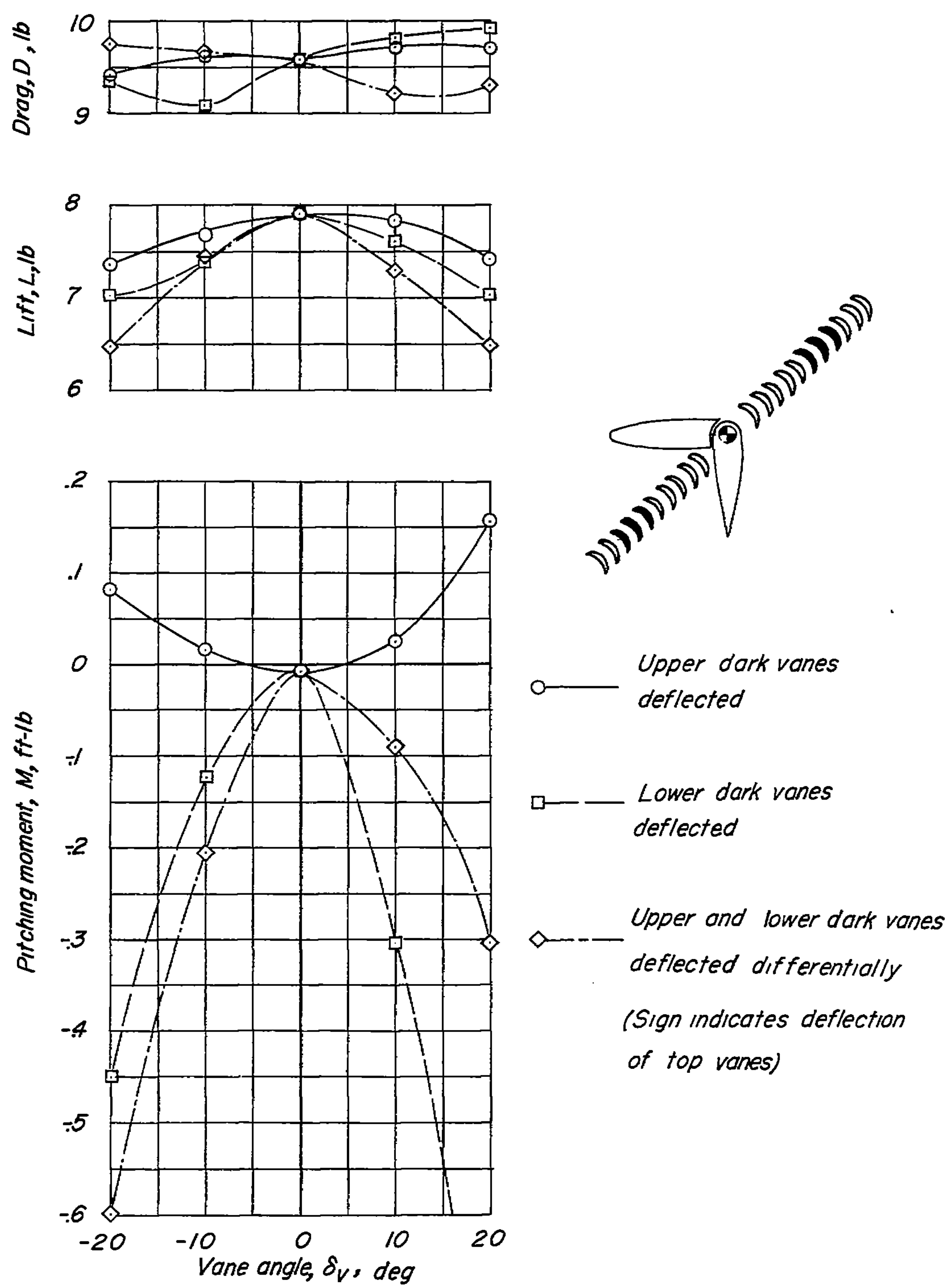

(a)

Figure 18.- Control effectiveness. Cascade angle (defined in fig. 17) = 45°.



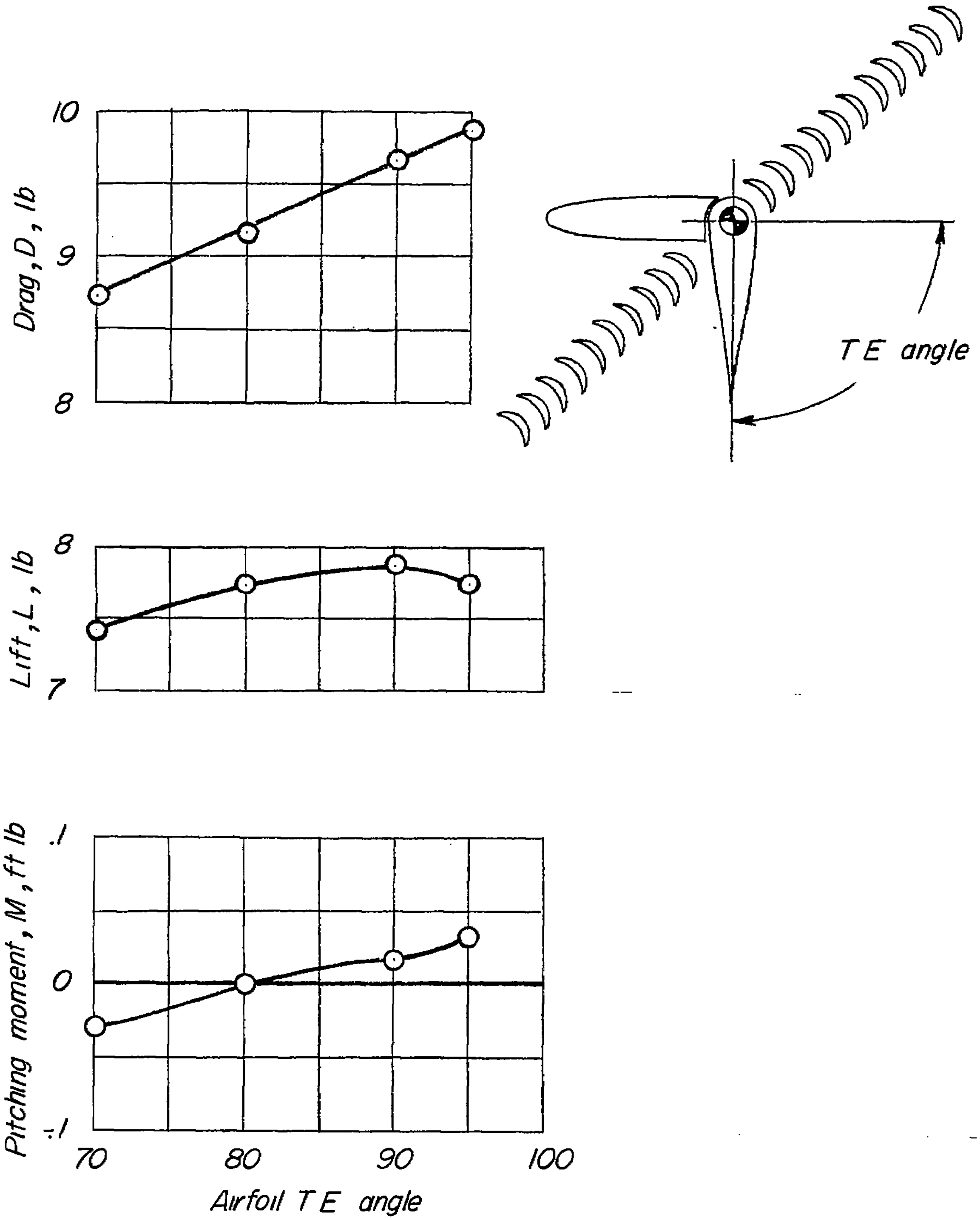

(b)

Figure 18.- Continued.



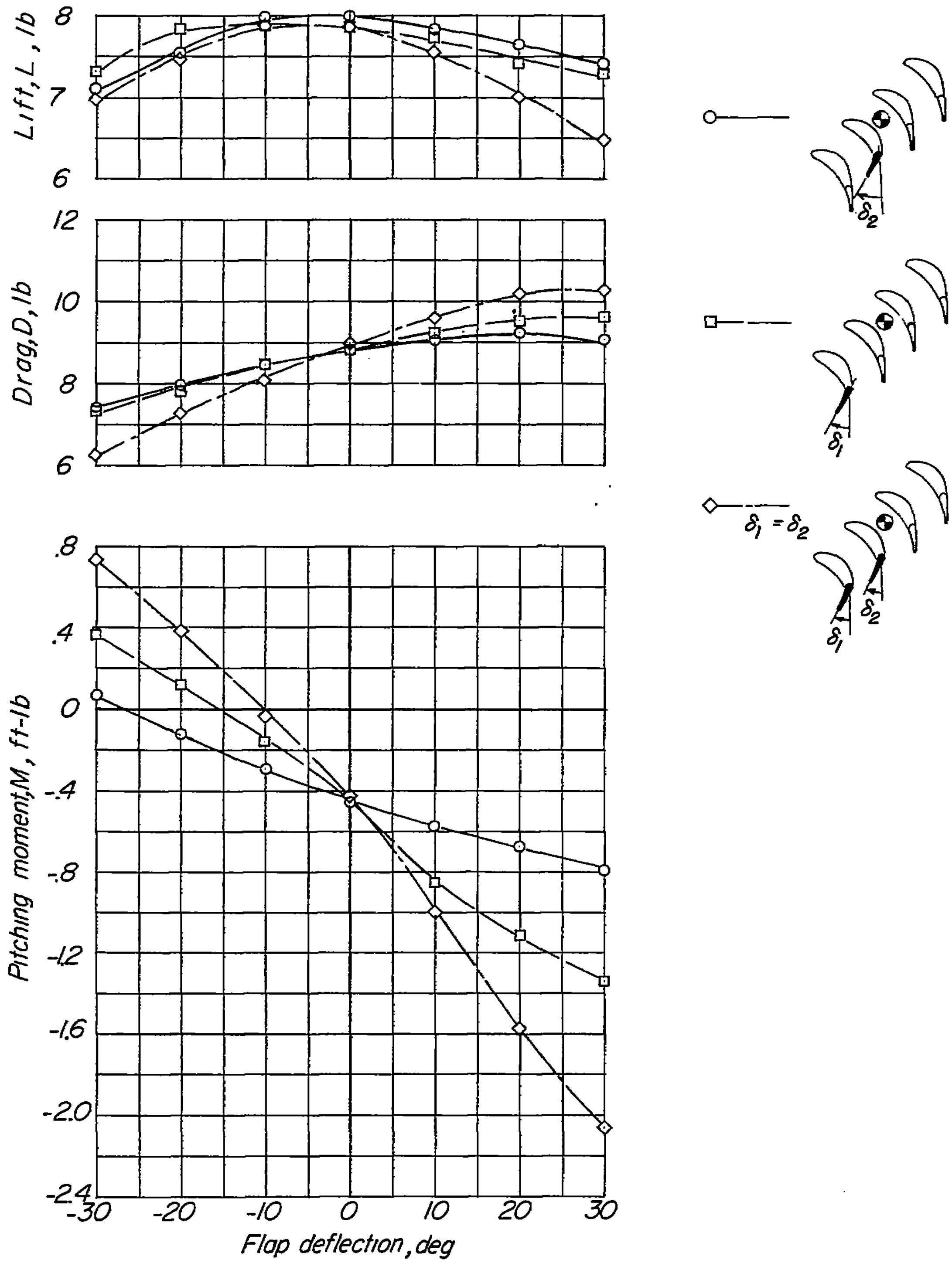

(c)

Figure 18.- Continued.



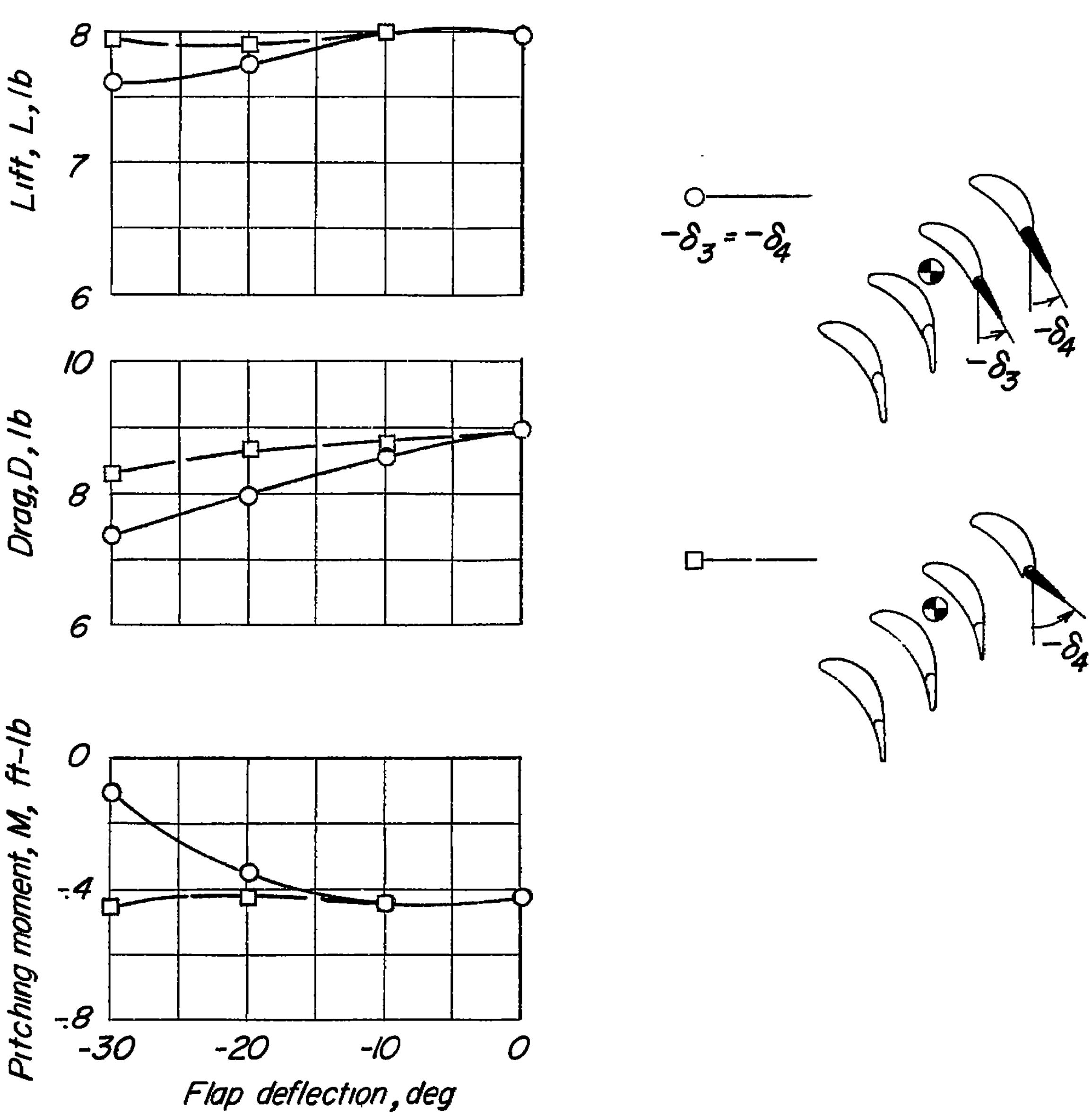

(d)

Figure 18.- Continued.



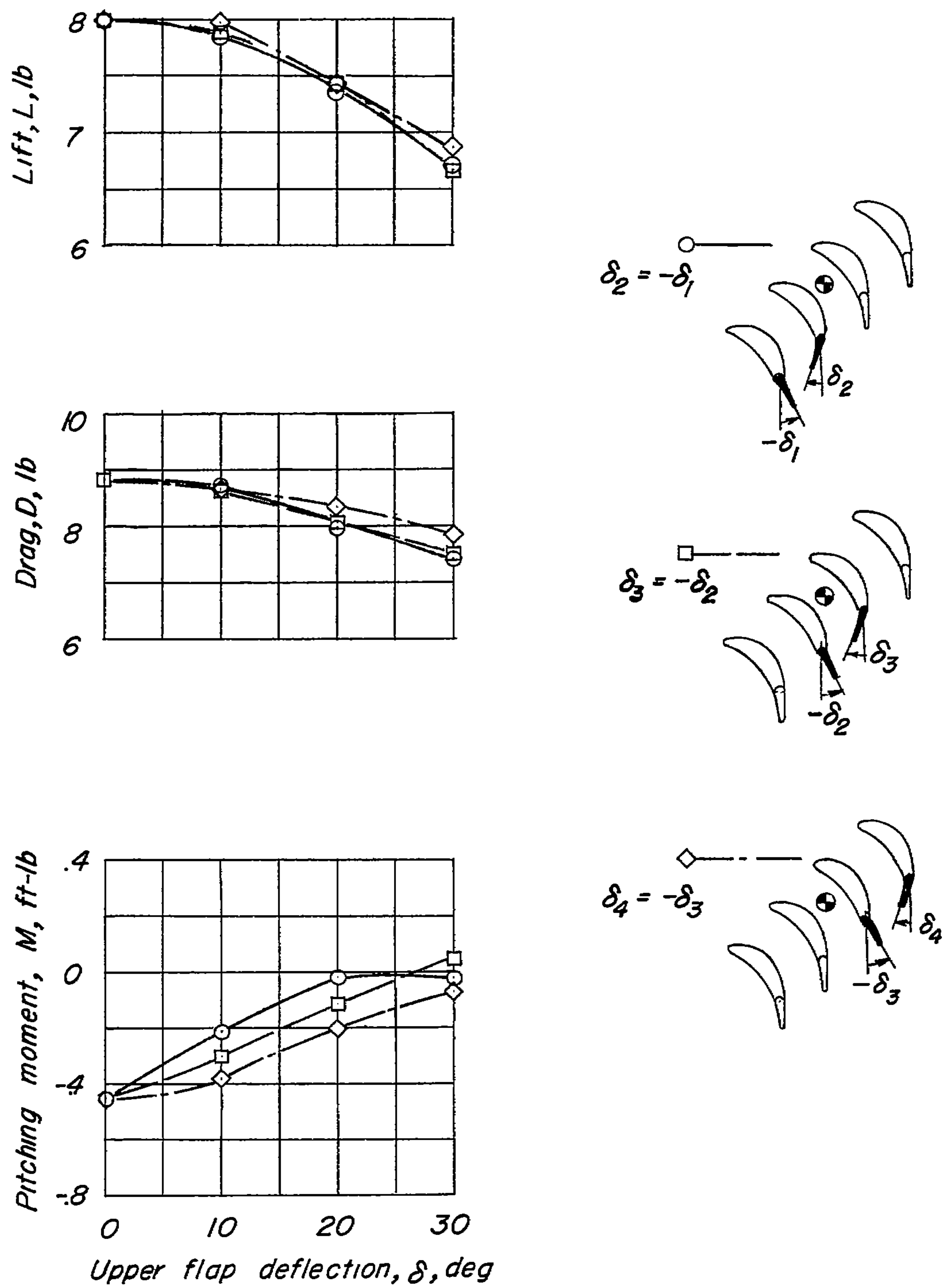

(e)

Figure 18.- Continued.



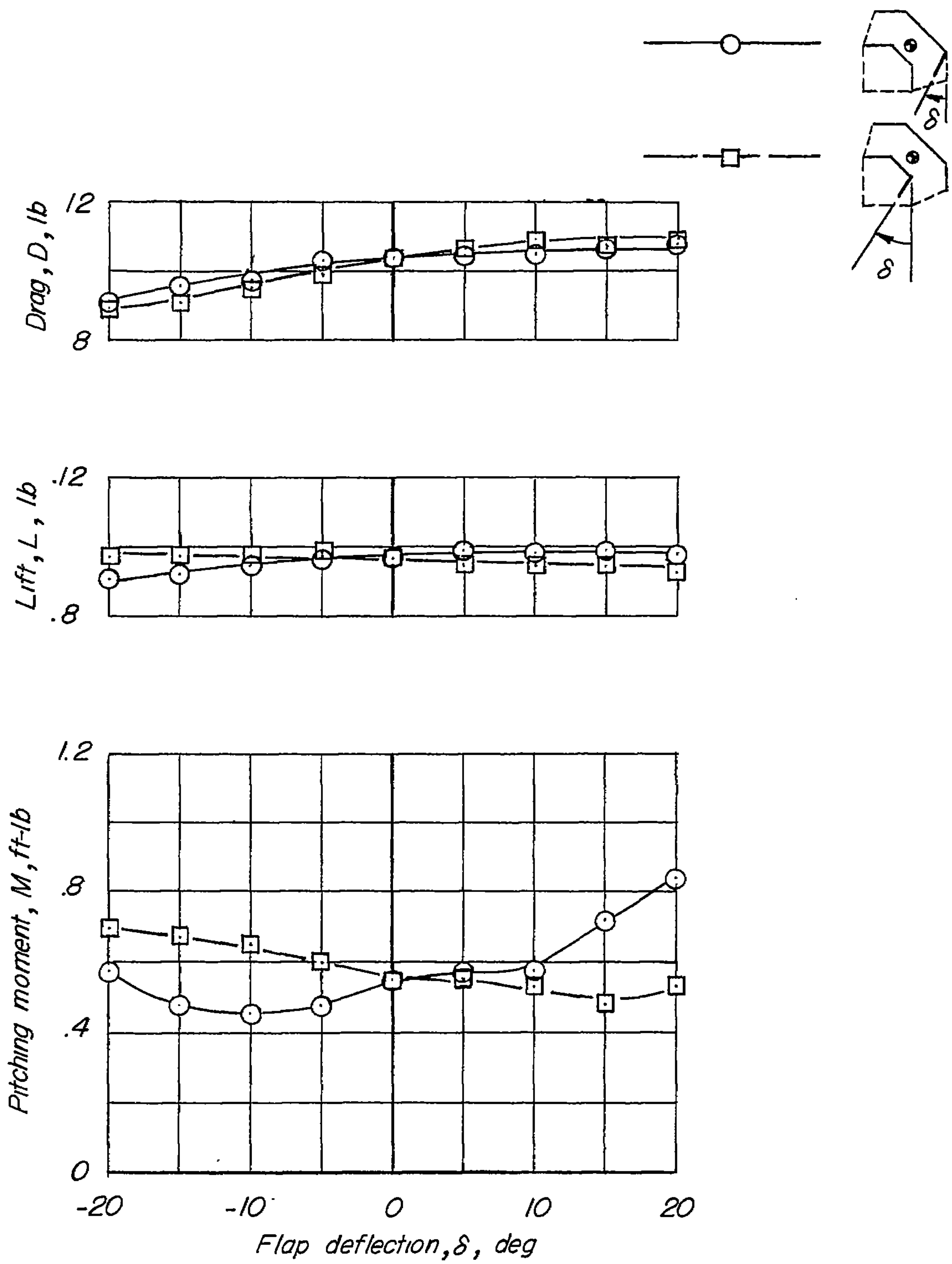

(f)

Figure 18.- Continued.



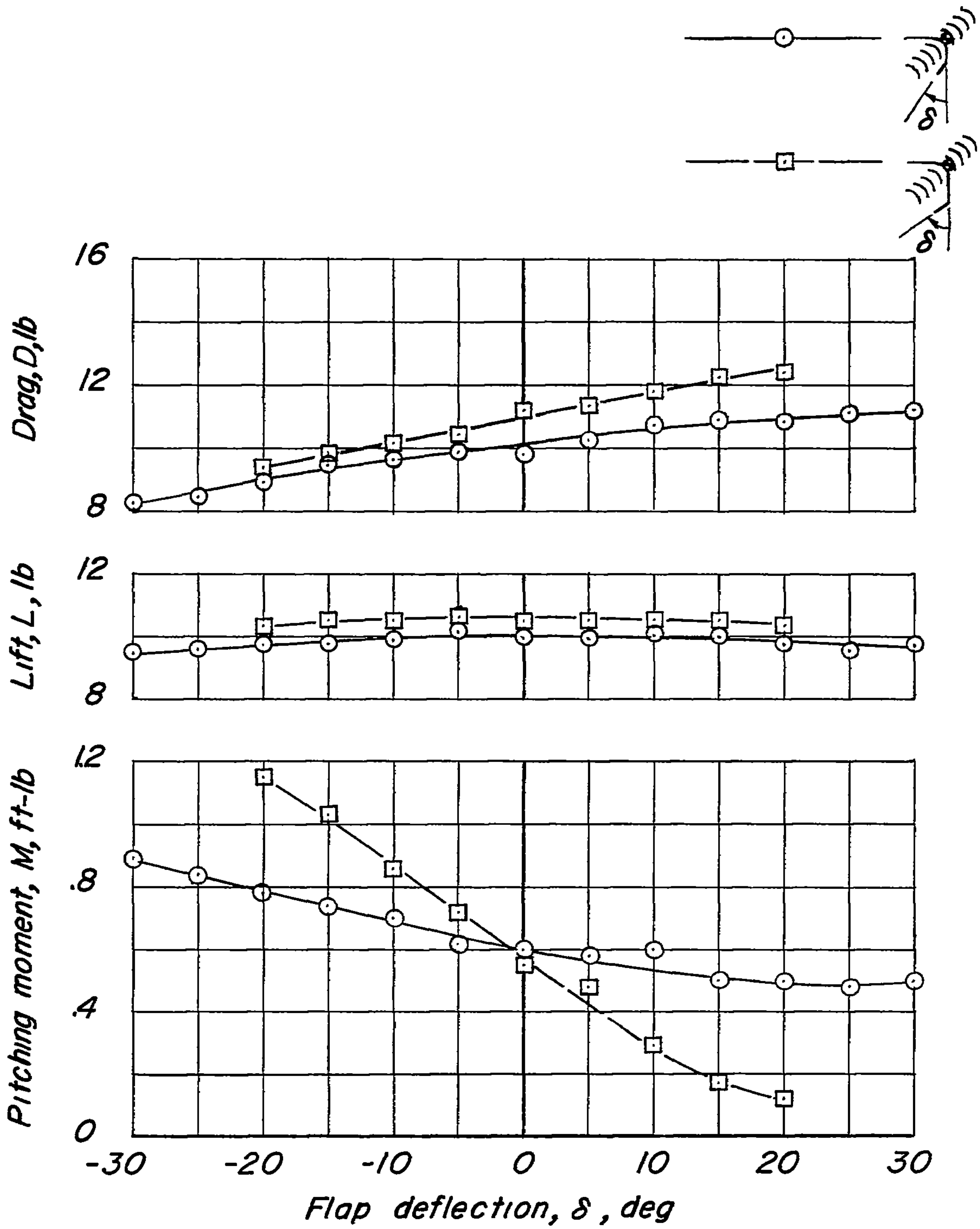

(g)

Figure 18.- Concluded.




(a) Configuration 6P.

Figure 19.- Control effectiveness.




(b) Configuration 2.

Figure 19.- Concluded.

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